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Sensor management for tactical surveillance operations

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Abstract

The military typically operate in large-scale, dynamic, and semi-structured environments. A key challenge facing the military operators in these contexts, is to make the most effective use of the available, but scarce, sensors to gather the most complete and relevant information. This defines the sensor management problem that aims at utilizing the sensing resources in a manner that synergistically improves the process of data acquisition and ultimately enhances the perception and the comprehension of the situation of interest. As part of the Command & Control process, sensor management is about the adaptive coordination, allocation, and control of sensing resources. This memorandum provides a state of the art on sensor management in the context of military tactical surveillance operations. In particular, issues and constraints associated with sensor management in scenarios involving a single sensor, multiple sensors aboard a single platform, and multiple sensors distributed across multiple platforms are discussed.

Résumé

Les forces militaires sont à l'oeuvre généralement dans des environnements à grande échelle, dynamiques et semi-structurés. L'un des principaux défis des opérateurs militaires dans cette situation est d'utiliser de la manière la plus efficace les capteurs disponibles, mais peu abondants, afin de colliger l'information la plus complète et la plus pertinente possible. Cela définit la problématique de la gestion des capteurs qui vise à utiliser les ressources de façon à perfectionner de manière synergique le processus d'acquisition des données et, au final, améliorer la perception et la compréhension de la situation d'intérêt. En tant que partie du processus de Commandement et Contrôle, la gestion des capteurs consiste en la coordination, l'allocation et le contrôle adaptatifs des capteurs. Ce mémorandum fournit un état de l'art sur la gestion des capteurs dans le cadre des opérations militaires de surveillance tactique. En particulier, les problèmes et les contraintes liés à la gestion des capteurs dans des scénarios impliquant un seul capteur, plusieurs capteurs à bord d'une seule plateforme et plusieurs capteurs distribués sur plusieurs plateformes sont discutés.

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Executive summary

Sensor management for tactical surveillance operations

A. Benaskeur, H. Irandoust; DRDC Valcartier TM 2006 - 767; Defence R&D Canada – Valcartier; November 2007.

This document is the first of a series that describes the results and findings of the project: *Planning and Control of Sensors for Adaptive Information Gathering in Distributed Environments: A Holonic Control Approach*. This project is part of the research activities conducted at Defence Research & Development Canada – Valcartier (DRDC Valcartier), which aim at defining, developing, and demonstrating sensor management and data fusion adaptation concepts in distributed, large-scale, and high-density military environments.

The military typically operate in dynamic, and semi-structured environments. In this context, sensors represent the main sources of real-time data, which by the process of data fusion, are integrated and interpreted to allow accurate inferences about the environment. A key challenge facing the military operators, in these contexts, is to make the most effective use of the available, but scarce, sensors to gather the most relevant information. This problem is addressed by the concept of sensor management. Its aim is to utilize the sensing resources in a manner that synergistically improves the process of data acquisition and ultimately enhances the perception and the comprehension of the environment.

Sensor management concerns the control and coordination of limited sensing resources in order to collect the most complete and accurate data from a dynamic scene. As such, sensor management is a key enabler of military surveillance. Sensor management may be thought of as closing the loop on the fusion process, whereby sensing resources are actively managed to improve the quality of inferences made about the environment.

The objective of this memorandum is to provide a state of the art on sensor management in the context of military surveillance operations. A review of tactical sensing with a focus on those sensors used by the Canadian Navy is provided. The concept of sensor management as a way of optimizing the use of the sensing resources and its role in the data fusion process is explained and elaborated with a focus on military applications. Then, issues and constraints associated with sensor management in scenarios involving a single sensor, multiple sensors aboard a single platform, and multiple sensors distributed across multiple platforms are exposed. Finally, the characteristics and constraints of sensor management in the military context are discussed.

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Sommaire

Sensor management for tactical surveillance operations

A. Benaskeur, H. Irandoust ; DRDC Valcartier TM 2006 - 767 ; Recherche et développement pour la défense Canada - Valcartier ; novembre 2007.

Ce document est le premier d'une série qui décrit les résultats et les points saillants du projet : *Planning and Control of Sensors for Adaptive Information Gathering in Distributed Environments : A Holonic Control Approach*. Ce projet fait partie des activités de recherche menées à Recherche et développement pour la Défense Canada – Valcartier (RDDC Valcartier) qui visent à définir, développer et démontrer les concepts de la gestion des capteurs et de l'adaptation de la fusion des données dans des environnements militaires distribués, à grande échelle et très denses.

Les forces militaires sont à l'oeuvre généralement dans des environnements dynamiques et semi-structurés. Dans ce cadre, les capteurs représentent la principale source des données en temps réel, lesquelles par le processus de la fusion des données, sont intégrées et interprétées afin de permettre des inférences sur l'environnement. L'un des principaux défis des opérateurs militaires dans ce cadre est d'utiliser de la manière la plus efficace les capteurs disponibles, mais peu abondants, afin de colliger l'information la plus complète et la plus pertinente possible. Cela définit la problématique de la gestion des capteurs qui vise à utiliser les ressources de façon à perfectionner de manière synergique le processus d'acquisition des données et, au final, améliorer la perception et la compréhension de l'environnement.

La gestion des capteurs consiste en le contrôle et la coordination de ressources (capteurs) limitées afin de colliger les données les plus complètes et les plus pertinentes à partir d'une scène dynamique. En tant que telle, la gestion des capteurs est l'un des éléments clé de la surveillance militaire. Elle peut être vue comme fermant la boucle sur le processus de la fusion, permettant ainsi d'améliorer la qualité des inférences produites en gérant activement les ressources.

Ce mémorandum fournit un état de l'art sur la gestion des capteurs dans le cadre des opérations militaires de surveillance tactique. Une revue des capteurs tactiques est présentée avec l'accent sur ceux utilisés par la Marine canadienne. Le rôle de la gestion des capteurs dans le processus de fusion des données est expliqué et l'utilisation de l'information de haut niveau pour l'optimisation des capteurs est illustrée par de nombreux exemples. Les problèmes et contraintes liés à la gestion des capteurs sont exposés par des scénarios impliquant un seul capteur, plusieurs capteurs à bord d'une seule plateforme, et plusieurs capteurs distribués sur plusieurs plateformes. Les caractéristiques et les contraintes de la gestion des capteurs dans le cadre militaire sont discutés.

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1 Introduction

In military operations, the Command and Control (C^2) process is one of acquiring information, interpreting the information, planning a course of action and finally implementing this action. This is often characterized by Boyd's Observe-Orient-Decide-Act (OODA) loop, as shown in Figure 1.

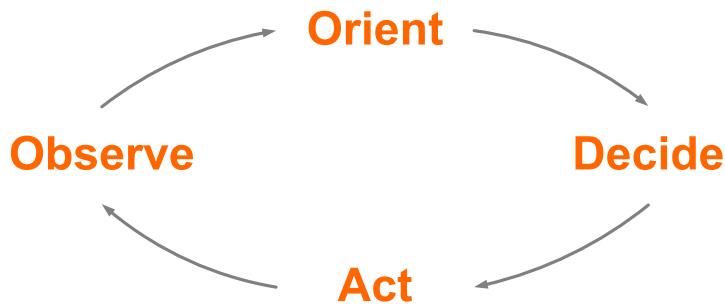


Figure 1: OODA loop

The military typically operate in demanding, dynamic, unstructured and large-scale environments. This reality makes it difficult to detect and track all targets within the Volume of Interest (VOI), thus increasing the risk of late detection of threatening objects and inappropriate/late response to them. This can be very critical to own-force survival in high target-density contexts, such as in littoral environments, hence the prime importance of surveillance operations and the underlying information gathering process.

The objective of military surveillance operations is to gather information about the presence and activity of all potential targets in the VOI. Surveillance is the systematic observation of a tactical situation by sensors. The data collected by the surveillance system are used by analysts, both human and software, to build a representation of the tactical situation. This representation can provide a detailed description of the environment (terrain, weather and any human-made structures), indicate the spatial coordinates of friendly, enemy or neutral targets, and even include temporal changes if the observation period is sufficiently long in duration.

Military platforms are generally outfitted with a suite of surveillance sensors that offer a wealth of data, provided they are properly managed. Those sensors collect, process and transmit information about the environment to planners, so that they can direct operations. A key challenge facing the military is how to make the most effective use of sensing resources to cover a certain VOI.

Interpreting the collected data as well as managing the sensing resources has historically been done manually. However, this task has grown difficult if not impossible due to the complex functionality of modern sensory systems. Current initiatives seek to automate the

process of data interpretation and sensor management. Data and information fusion is a concept whereby data from various sources are integrated and interpreted to allow accurate inferences about the environment. The idea is that fusing data from numerous sources provides a better picture of the environment than inferring from sensor measurements independently. Dual to data fusion is the concept of sensor management. Its aim is to utilize the sensing resources in a manner that synergistically improves the process of data acquisition and ultimately enhances the perception and the comprehension of the situation of interest.

Sensor management concerns the control and coordination of limited sensing resources in order to collect the most complete and accurate data from a dynamic scene. As such, sensor management is a key enabler of military surveillance. Sensor management may be thought of as closing the loop on the fusion process, whereby sensing resources are actively managed to improve the quality of inferences made about the environment.

This document is the first of a series that describes the results and findings of the project: *Planning and Control of Sensors for Adaptive Information Gathering in Distributed Environments: A Holonic Control Approach*. This project is part of the research activities conducted at Defence Research & Development Canada – Valcartier (DRDC Valcartier), which aim at defining, developing, and demonstrating sensor management and data fusion adaptation concepts in distributed, large-scale, and high-density military environments. The objective of the current memorandum is to establish the role of sensor management within the paradigm of data fusion; to explain the function of sensor management in the context of surveillance operations, and to discuss the challenges faced by sensor management in military settings.

This memorandum is divided into several chapters. Chapter 2 presents tactical surveillance sensors used by the military and their basic characteristics. Chapter 3 describes the data fusion paradigm and the role of sensor management. It also presents the advantages of using sensor management in military target tracking applications. In Chapter 4, general considerations with respect to sensor management in the military context are discussed. Issues related to specific situations are presented through scenarios involving the management of a single sensor, of co-located sensors and of distributed sensors. Finally, Chapter 5 discusses the hierarchical and recursive nature of sensor management problems.

2 Characteristics of tactical sensors

Fundamentally, a sensor is a device that responds to certain physical stimuli and should not influence the events or the environment under surveillance. Simple sensors are incapable of assessing or understanding the response to the stimuli that they observe and transmit. A sensor can merely report an event or change in the environment. Some of the characteristics of sensors in general are presented in Table 1. These characteristics define the performance of a given sensor. Among these characteristics, accuracy, range, resolution, update rate and field of view are the most pertinent to sensor management. This is not to say that the other characteristics will not have an impact on sensor management, but that they will do so in a less significant way, depending upon the individual sensing system.

Table 1: Sensor characteristics

Characteristic	Description
Accuracy/Precision	The correctness of the measured absolute value or event
Drift	The degree to which the measured value shifts away from the correct value over time
Dynamic range	The allowed lower and upper limits of the instruments' input or output given the required level of accuracy
Reliability	The ability to consistently return correct measures
Resolution	The finest measurable change in input value
Repeatability	The ability to consistently return the same measure for the same input conditions
Update rate	The rate at which a new signal value is collected
Sensitivity	A qualitative assessment of sensor performance that is typically a combination of range and resolution
Signal to noise ratio	The ratio between the measured value component and the noise value component of the signal
Steady state error	The error between the measured value and the absolute value
Aperture	The size of the opening that allows light or electromagnetic radiation pass to the sensor.

Field of view The segment of the observable space relative to the entire space. The Field Of View (FOV) can range from omnidirectional to point focus, depending on other sensor characteristics

Tactical sensors are those used by the military to detect, classify and track targets of interest that may be friend, neutral or enemy. A radar system is a fairly common tactical sensor used to detect a target at a distance. Advanced radar systems are coupled with sophisticated processing equipment that can allow them to monitor and track multiple targets, classify targets based on known characteristics and search for any new targets entering the VOI.

Tactical military sensors provide kinematic data (*i.e.* position, heading, speed, acceleration, etc.) and non-kinematic data (*i.e.* identity, radar cross section, IR signature, etc.) for a given target under surveillance. Although tactical sensors are capable of monitoring events to their highest sensitivity, typically they operate with a certain threshold and only report events that exceed this level, commonly referred to as a “contact”. This approach is taken to reject noise so as not to overload the data fusion system with spurious contacts.

The scale of surveillance operations varies depending on the branch of the military undertaking the operation. The army tends to undertake localized surveillance and relies heavily on human sensors and sensors with limited range, while the navy and air force tend to work in a much larger space, with sensors that can observe targets up to hundreds of kilometers away. This scale factor appears to be proportional to the effective range of available weaponry and the speed at which a physical presence can be relocated. The generalized suite of tactical surveillance sensors available today is presented in Table 2. The range scale is as follows: Short (0 m to 100 m), Med (100 m to 10 km), and Long (10 km to 1000 km).

Table 2: Surveillance sensor categories

	Sensor	Range	Mode
Human (eye, ear, nose)		Short	Passive
Radar	Med/Long	Active	
Thermal imagery	Short/Med	Passive	
Optical imagery	Short/Med	Both	
Sonar imagery	All	Both	
Lidar	Short/Med	Active	
ESM	Med/Long	Passive	
Radio transmission direction finding (DF)	Med/Long	Passive	
MAD	Short/Med	Passive	
Chemical & biological sensors	Short	Both	
Radiation detector	Short	Passive	
Geophone (seismic activity)	All	Passive	
Acoustic sensor (microphone)	Short	Passive	
Hydrophone	Short/Med	Passive	

2.1 Active and passive sensors

In situations where the target of interest does not emit sufficient Electro-Magnetic Radiation (EMR) to be detected, the region where the target is believed to be in can be flooded with the appropriate type of EMR allowing the reflected or excited response by the target to be observed with the sensor. For example, a camera in a dark area requires a flash to illuminate the area sufficiently so that a picture can be captured. If the flash is not used, then the captured picture will be of very poor quality and most likely useless. Sensing systems that are coupled with some form of emitter are considered active (for example, radar). The consequence of using active sensor systems is that the environment is modified in some way, thus affecting the scene being observed. With active sensor systems, it becomes possible for the target under observation to observe you as well.

Passive sensors can be used covertly as they do not announce their presence to others; therefore, the surveillance of the target is not corrupted by the target reacting to an outside stimulus. Active sensor systems can provide detailed data, but at the same time, they can influence the behavior of the target if the latter knows that it is under surveillance. The appropriate use of active sensors is determined by the policies provided to the sensor management system in terms of mission constraints.

2.2 Environmental impacts

The environment can significantly influence the performance of surveillance sensors. Some of the environmental conditions that can have an impact on sensor performance are: light level, temperature, humidity, wind, dust, direct sunshine, rain, snow, ice, and water (immersion: partial or full). For instance, light level is important for any optical imaging. If the area under observation is not sufficiently lit, then it may not be possible to observe the targets. Heavy rain and snow will have an impact on the radar images, as a function of frequency, raising the clutter level to a point where it can obscure or greatly reduce the probability of detecting targets. Secondary to influencing the sensors' observation capacities, the environment can impact the operations of sensors mechanically and electrically, preventing them from functioning or making them report erroneous signals. Damage to the sensor itself from dust, ice, water, freezing or overheating is a hazard that can be mitigated through careful selection of the sensor with regard to the operational environment. For instance, it would be unwise to install a sensor that can not be exposed to water on the deck of a ship without suitable protection and regular inspection.

Different types of sensors detect different regions of the electromagnetic spectrum. A target that is observable with one type of sensor may not be so with another. A target that is visible to radar at night will not be visible with optical sensors, but it may be visible to thermal infrared if it has a heat signature. On the other hand, a wooden structure that may not be visible to radar, would be visible to optical sensors.

2.3 Sensors and platforms

All sensors require some form of support infrastructure to operate (power, personnel, and physical structure). Unless a sensing resource is truly stationary, such as a large radar station, sensors typically are installed on military platforms, such as aircraft, ships, tracked and wheeled vehicles, and satellites. Each sensor system has a given physical size and weight and needs a certain amount of power to operate. Thus, when selecting a suitable sensor for use on a particular platform, trade-offs have to be made. A small platform such as an Unmanned Aerial Vehicle (UAV) has limited payload capacity and power budget; therefore, UAVs are limited to carrying only light weight and low power sensors such as optical cameras, thermal InfraRed (IR) cameras, Laser IR Radar (LIDAR). In comparison, a ship is a large platform with a large payload capability and a large power budget. Therefore, it can support large and high power sensors, such as: multiple long range radar systems, multiple sonar systems, and a large crew complement that are all equipped with the best sensors available (eyes, ears, touch, and smell). Humans are adept at monitoring regions in their immediate vicinity. The sense of sight can be extended with the use of optics: binoculars, night vision equipment, etc. Table 3 presents a summary of the types of surveillance sensors used on Canadian Forces military platforms.

Note that “●” corresponds to a known availability, and “○” to a probable or future availability. Also, typically a UAV has limited payload capacity and power budget; therefore, it is unlikely that a UAV can support all of these sensors simultaneously and would rather carry only one or two of these sensors during a given mission. The payload bay of a UAV is capable of supporting multiple types of payloads and the sensor suite elements can be changed depending on mission requirements.

Table 3: Sensing platforms and sensors

	Iroquois	Halifax	CP-140	CH-124	Kingstone	Victoria	UAV
Human	●	●	●	●	●	●	
Radar	●	●	●	●	●	●	●
IR imagery		○	●	●			●
Vis imagery			●	●	○	○	●
Sonar	●	●		●		●	
Lidar							○
ESM	●	●	●	○		●	○
DF	●	●	●			○	
MAD			●	●			○
IFF ¹	●	●	●	●	○	○	○
Chem/Bio	○	○					○
Radiation	○	○					○

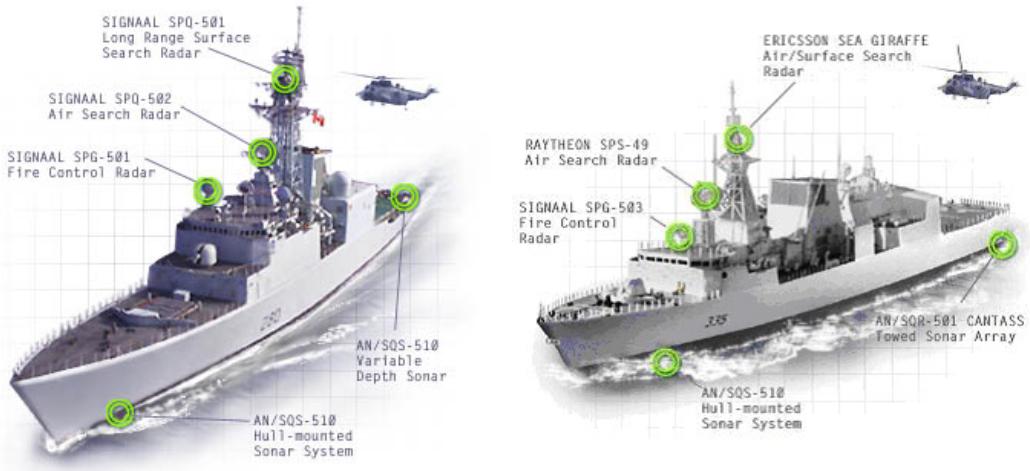
¹Identification Friend or Foe

For illustration purposes, the following figures and tables present several of the tactical sensors deployed in select Canadian Forces naval military platforms.

Table 4: Canadian Navy Iroquois Class Destroyer tactical sensors

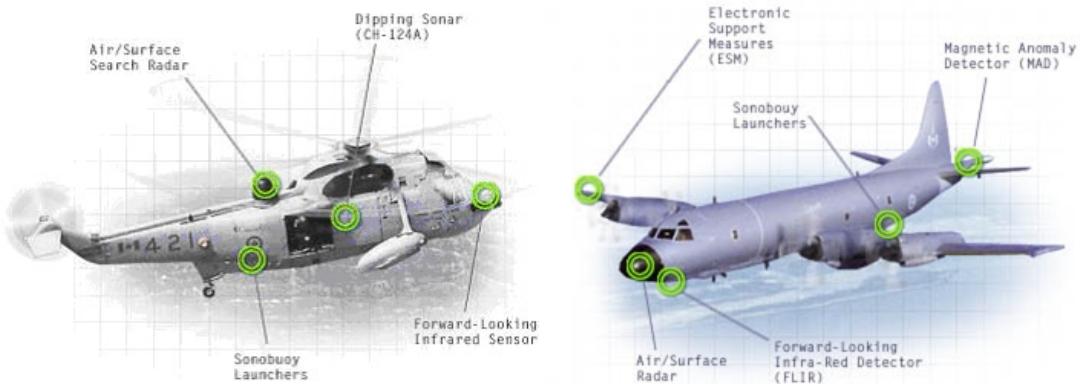
Sensor	Description	Mode
SPQ-501 DA-08	Thales 2D air and surface surveillance radar in F-band for medium and long ranges (135/270km)	Active
SPQ-502 LW-08	Thales A high-power coherent D-band long range surveillance radar (270km)	Active
SPG-501 STIR 1.8	Thales Fire control radar for missile and gun, tracking small, fast surface threats I-band [range, bearing, altitude, IFF data] maximum range 140 km	Active
Type 1007	Navigation Radar [range, bearing] maximum range 84 km	Active
AN/SQS-510 General Dynamics	Hull-mounted active and passive sonar and variable depth active and passive sonar for submarine and torpedo detection, and mine avoidance. [range, bearing] range 1.8 km to 55 km	Active or Passive
AN/SLQ-501 CANEWS Canada	LM Electronic Support Measures (ESM) CANEWS ² for detecting, intercepting, identifying, and locating sources of radiated electromagnetic energy. [bearing, classification] maximum range 1000 km	Passive
AN/SRD-502 South West Research Institute	Communication interception and direction finding (DF) unit [bearing, classification] maximum range 1100 km	Passive
Cameras (day-light/ night-vision) (video & still)	Record optical and infrared still images or motion video of events for near-real time assessment or long term analysis and archiving. Range is limited by the image resolution and the optics used; it is typically limited to a few kilometres	Active or Passive

²Canadian Naval Electronic Warfare System.



(a) Iroquois Class Destroyer

(b) Halifax Class Frigate



(c) CH-124 Sea King Helicopter

(d) Aurora (CP-140)



(e) I-GNAT UAV

Figure 2: Canadian Navy sensors

Table 5: Canadian Navy Halifax Class Frigate tactical sensors

Sensor	Description	Mode
Ericsson SeaGiraffe HC150	A G-band Air/Surface search radar capable of providing accurate tracking data to the ships Combat Information Centre and weapons system [range, bearing, IFF data] max range 100 km	Active
Raytheon SPS-49(V)	A high-power coherent C/D very long range two-dimensional surveillance radar [range, bearing, IFF data] maximum range 460 km	Active
SPG-501 Thales/Signaal STIR 1.8	Fire control radar for missile and gun, tracking small, fast surface threats I-band [range, bearing, altitude, IFF data] maximum range 140 km	Active
Type 1007	Navigation Radar [range, bearing] maximum range 84 km	Active
AN/SQS-510 General Dynamics	Hull-mounted active and passive sonar and variable depth active and passive sonar for submarine and torpedo detection, and mine avoidance [range, bearing] range 1.8 km to 55 km	Active or Passive
AN/SQR-501 CANTASS General Dynamics Canada	A critical angle low frequency towed array sonar system provides frequency and bearing analysis of acoustic emission from long ranges and is consistent in both shallow water and beyond the second convergence zone. [bearing]	passive
AN/SLQ-501 CANEWS LM Canada	Electronic Support Measures (ESM) CANEWS for detecting, intercepting, identifying, and locating sources of radiated electromagnetic energy. [bearing, classification] max range 1000 km	Passive
AN/SRD-502 South West Research Institute	Communication interception and direction finding (DF) unit [bearing,classification] maximum range 1100 km	Passive
Cameras (daylight/night-vision) (video & still)	Record optical and infrared still images or motion video of events for near-real time assessment or long term analysis and archiving. Range is limited by the image resolution and the optics used; it is typically limited to a few kilometres	Active or Passive

Table 6: Canadian Navy Sea King (CH-124) helicopter tactical sensors

Sensor	Description	Mode
cameras (day-light/ night-vision) (video & still)	Record optical and infrared still images or motion video of events for near-real time assessment or long term analysis and archiving. Range is limited by the image resolution and the optics used; it is typically limited to a few kilometres	Active or Passive
FLIR	Forward looking infrared	Passive
Radar	Area surveillance and threat detection radar	Active
Dipping sonar	A sonar system that is lowered into the water column. A typical depth capability of 120m	Active or Passive
Sonar buoys	Air or ship deployable sonar system. When deployed by aircraft, they extend the sensing capabilities to the realm below the surface of the water. When deployed by ships or support helicopters, it extends the sensing area and allows them to move off station while monitoring an area	Active or Passive
Magnetic Anomaly Detector (MAD)	A device for detecting changes in the earth's magnetic field, indicating the presence of a large metal object, such as a submarine	Passive

Table 7: Canadian Navy Aurora (CP-140) tactical sensors

Sensor	Description	Mode
cameras (day-light/ night-vision) (video & still)	Record optical and infrared still images or motion video of events for near-real time assessment or long term analysis and archiving. Range is limited by the image resolution and the optics used; it is typically limited to a few kilometres	Active or Passive
MX-20	An electro-optical/forward-looking infrared (FLIR) imager	Passive

Radar	Area surveillance and threat detection radar	Active
Sonobuoys	Air deployable sonar system. When deployed by aircraft, they extend the sensing capabilities to the realm below the surface of the water, and allow the aircraft to move away from the area being monitored.	Active or Passive
AN/APS-143	Inverse synthetic aperture radar (SAR)	Active
Magnetic Anomaly Detector (MAD)	A device for detecting changes in the earth's magnetic field, indicating the presence of a large metal object, such as a submarine	Passive
ESM	For detecting, intercepting, identifying, and locating sources of radiated electromagnetic energy	Passive

Table 8: I-GNAT UAV tactical sensors

Sensor	Description	Mode
Cameras (day-light/ night-vision) (video & still)	Record optical and infrared still images or motion video of events for near-real time assessment or long term analysis and archiving. Range is limited by the image resolution and the optics used; it is typically limited to a few kilometres	Active or Passive
FLIR	Forward looking infrared	Passive
Radar	Area surveillance and threat detection radar	Active
SAR	Synthetic Aperture Radar	Active
Magnetic Anomaly Detector (MAD)	A device for detecting changes in the earth's magnetic field, indicating the presence of a large metal object, such as a submarine	Passive
ESM	For detecting, intercepting, identifying, and locating sources of radiated electromagnetic energy	Passive
Radiation Detector	A device for detecting the level of radioactivity in the immediate area to ascertain if levels are a danger to humans and animals	Passive

Chemical & biological agent detector	A device for detecting trace levels of chemicals and biological agents that may be harmful to troops and other personnel in the immediate vicinity	Passive
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2.4 Operational issues

The use of sensors in a military tactical setting presents certain operational issues as listed in Table 9.

Table 9: Tactical operational sensor issues

Operational Issue	Description
Cost	The dollar value associated with the sensor including: purchase cost, training cost, scale of platform required
Value	The importance or significance of the data being collected
Detectability	The ability to detect the presence of a sensor (does the sensor emit a detectable characteristic signal) by the opposing force
Maintainability	The ease of installation, maintenance/repair, and replacement
Man-power required	The man-power required to operate and maintain a particular sensor or sensor suite
Communications	Communications between the sensor and the system monitoring it is governed by bandwidth, data format, transmission protocol and transmission media
Portability	The ease with which the sensor can be relocated and used from a mobile platform
Power	The type and amount of power required by the sensor to operate and communicate
Robustness	The ability to survive the sensing environment and withstand damage while in transit (shock and vibration)
Susceptibility to motion	The ability of the sensor to be used from a moving carrier
Interference	Certain types of sensors can interfere with the operation of other sensors

Of these operational issues, detectability, communications, power and interference are the most relevant to sensor management.

The detectability of a sensing resource by an adversary is a factor that one typically wishes to minimize. This can be achieved by minimizing the energy radiated by the resource and making all necessary emissions follow a pseudo-random schedule. Sensor management would be responsible for implementing a low emission strategy.

Some of the communication issues associated with sensors are: bandwidth, data format, transmission protocol, and transmission media. For organic sensors, those resident on a single platform, the communications bandwidth is not usually an issue because the transmission media for local sensors is copper wire or fibre optics. For non-organic sensors, those located on another platform, communications between platforms is limited to a wireless tactical link that has limited bandwidth and functional range. Therefore, if a non-organic data stream is being incorporated into the data fusion process, these limitations must be considered in the planning and use of such data. Note that the Canadian Forces (Navy) make use of Link 11 as the wireless tactical link to connect data streams between platforms.

Power to operate sensing resources is not a great concern for large platforms such as ships and land-based systems, unless their supply chain is compromised in some way. However, for smaller platforms, such as helicopters and UAVs, there is a finite power budget and it must be used judiciously to ensure maximum mission length and maximum amount of information gathering.

Certain types of sensors can interfere with others. Sensor management must ensure that a sensor that emits some form of energy (acoustic, electromagnetic, and light) is not used when it can either damage another sensor or corrupt its data stream, potentially leading to a misinterpretation of the situation.

2.5 Smart sensors

Smart or intelligent sensors, as opposed to simple sensors that do not reason, perceive, reason and report. A smart sensor is one that incorporates some processing that allows it to discriminate between stimuli that are acceptable and those that are not. A smart sensor incorporates the first tier of data reduction within itself and eliminates the need to transmit large amounts of raw data to a secondary processor, when it is not necessary. The use of smart sensors has an impact on a sensing network because it lowers the communications bandwidth requirements. In a tactical setting, this reduced bandwidth requirement lowers: the communication time, the scale of the communications infrastructure, and possibly the probability of detection and interception of the transmission by enemy forces.

Most of the sophisticated surveillance sensors can be classed as smart sensors because they perform some level of processing and report only events or targets of interest. In the case of

an advanced radar system, the detection and tracking of a target entering the observation zone and the rejection of background clutter to enhance a target, would be considered smart. A broken optical beam that detects an object passing through a perimeter that is being monitored, cannot report if something either entered or left the area, nor can it discern if it was a human intruder or a rabbit. Therefore, the light beam is a simple sensor; it can merely report the event. However, as shown in Figure 3, by using several light beams the direction of travel and the height of the target can be inferred.

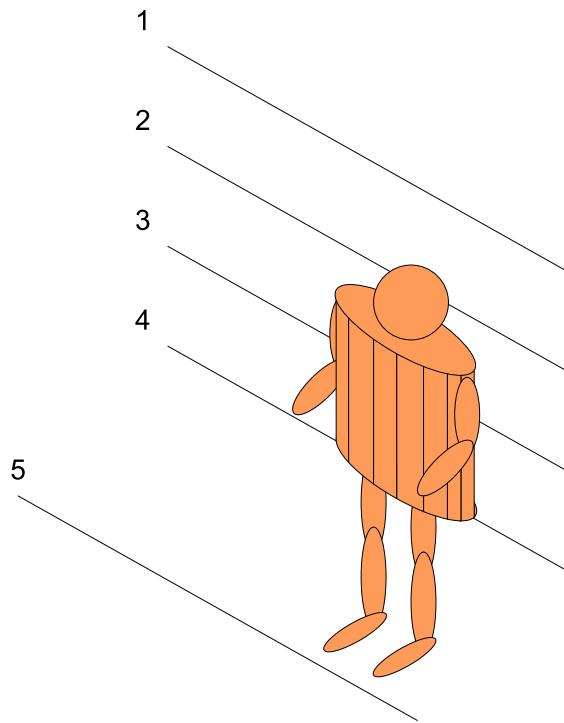


Figure 3: Intruder detection

In this example the height of the intruder can be estimated from the known heights of beams 1 and 2. The direction of travel can also be determined by which of beams 4 or 5 is broken first. Thus, multiple simple sensors can be setup to work together to collect simultaneous data streams that, when fused together, can allow for inference about the event under observation.

2.6 Multi-mode sensors

Today's military Command, Control, Communications, Computers, Intelligence Surveillance and Reconnaissance (C4ISR) systems employ a vast array of sensors to monitor a long list of parameters that define the battlespace. Advanced sensing technology enables the design and use of multi-mode sensors. Multi-mode sensors allow for the reconfiguration of key sensor parameters to enable the sensor to collect data over a wider range than is possible for a single sensor.

The CP-140 Aurora is currently undergoing an upgrade of its radar system and will be equipped with inverse synthetic aperture radar (SAR) to allow for the collection of larger data sets and to view targets in greater detail (Figure 4)³. SAR needs to be moved relatively to the environment. This is achieved through the movement of the aircraft; however, things can become complicated if the target under surveillance is also moving. Advanced SAR processing techniques can be employed to minimize these effects and recover the desired data. SAR also has the advantage that it can be operated in different modes, depending on the desired data set and the type of surveillance being undertaken.



Figure 4: Aurora CP-140 synthetic aperture radar

For illustration purposes, the operating modes of RADARSAT-1 based on SAR are presented here. SAR, an active sensing technique, allows radar images to be captured day or night in virtually all weather conditions. To make the data stream useful to the largest number of applications, RADARSAT-1 can be configured to scan in different modes and different look angles by selectively turning on and off certain beams. There are seven basic modes of operation, and each of those modes has beam selection to ensure coverage of the target area. Although not a tactical surveillance sensor, it is used as a strategic surveillance sensor on a nearly constant basis.

Figure 5⁴ and Table 10⁵ describe the modes of operation for RADARSAT-1.

³From www.sfu.ca/casr/101-cp140sar1.htm

⁴From http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/specs/radspec_e.html

⁵Adapted from table in http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/specs/rsattabl_e.html#standarddetails
Provided courtesy of the Canadian Space Agency

Table 10: RADARSAT-1 SAR operating modes

SAR modes	# of Beams	Nominal Swath Width [km]	Nominal Range from nadir [km]	Swath offset	Range Resolution [m]	Azimuth Resolution [m]
Standard 250 km nadir offset	7	100	1: 0-100		26	
			2: 60-160		22	
			3: 140-240		27	
			4: 210-310		25	28
			5: 280-380		24	
			6: 340-440		22	
			7: 400-500		21	
Wide-swath 250 km nadir offset	3	150	W1: 0-150		35	
			W2: 145-295		27	28
			W3: 290-420		23	
Fine-resolution 500 km nadir offset	5	50	F1: 0-50		9	
			F2: 45-95		97	
			F3: 90-140		9	9
			F4: 135-185		8	
			F5: 170-220		8	
SCANSAR wide		500	W1, W2, W3, 7		100	100
		440	W1, W2, 5,6			
SCANSAR narrow		300	W1, W2 W2, 5,6		50	50
			EH1 EH2 EH3 EH4 EH5 EH6			
Extended High 500 km nadir offset	6	75	EL1		25	28
Extended low 125 km nadir offset	1	75				

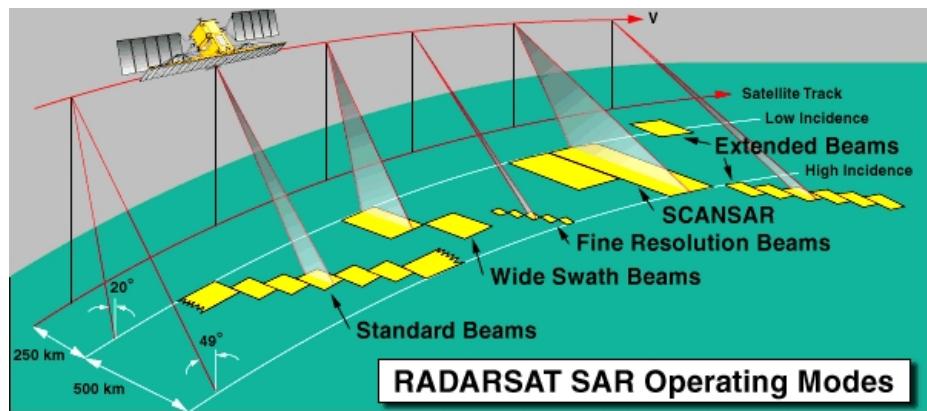


Figure 5: RADARSAT-1 SAR operating modes

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3 Data fusion & sensor management

Data and information fusion problems have been addressed in a number of research fields [1, 2]. More recently interest in automated data fusion processes has been the subject of interest in a variety of fields including the military. Current practices in data fusion involve a mixture of human and automated process, although efforts continue to develop greater automation.

Part of this automation effort is the concept of sensor management. Sensor management aids data (sensor) fusion by directing sensing resources in an adaptive manner as to acquire data that are relevant to mission objectives. The role of sensor management is to support the whole process of compilation, refinement, and interpretation of the tactical picture. This role is dynamic and must respond to changing conditions in the environment.

In an attempt to unify the terminology associated with data and information fusion, the U.S. Joint Directors of Laboratories (JDL) Data Fusion Group developed the JDL fusion model [3]. With subsequent revisions, it is the most widely used system for understanding data fusion processes. The goal of this model is to facilitate understanding and communication among researchers, designers, developers, evaluators and users of data and information fusion techniques to permit cost-effective system design, development and operation. A reviewed JDL data fusion model is illustrated in Figure 6. The JDL model differentiates data fusion functions into a set of fusion levels and provides a useful distinction among data fusion processes that relate to the refinement of “objects,” “situations,” “threats” and “processes.”

The generalized definitions of the levels are as follows (from [1]):

Level 0 (Sub-Object Data Assessment) – estimation and prediction of signal or object-observable states on the basis of pixel/signal level data association and characterization.

Level 1 (Object Assessment) – estimation and prediction of entity states on the basis of inferences from observations.

Level 2 (Situation Assessment) – estimation and prediction of entity states on the basis of inferred relations among entities.

Level 3 (Impact Assessment) – estimation and prediction of effects of planned or estimated/predicted actions by the participants (*e.g.*, assessing susceptibilities and vulnerabilities to estimated/predicted threat actions, given one’s own planned actions)

Level 4 (Process Refinement) – an element of resource management that deals with adaptive data acquisition and processing to support mission objectives.

The following paragraphs briefly describe these levels. More detailed description of these definitions can be found in [1, 3].

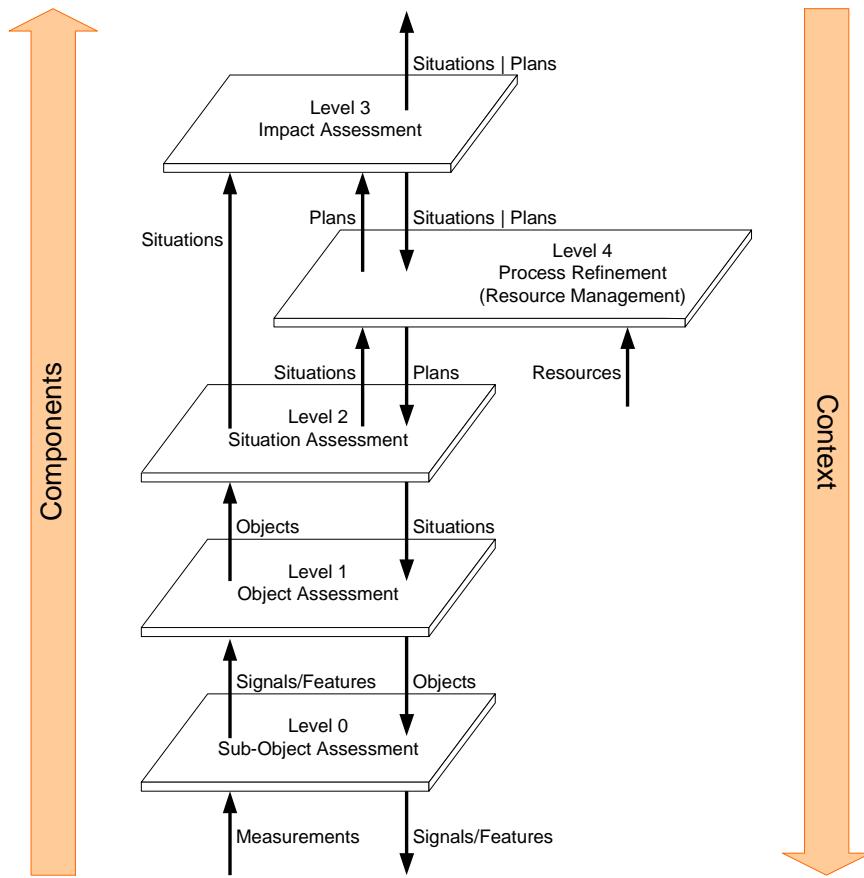


Figure 6: JDL data fusion model

As an example, consider the case of a platform outfitted with a variety of sensing resources. With respect to sensing, the platform is concerned with detecting, identifying and tracking objects within a Volume Of Interest (VOI). The platform's sensors will generate raw signals or measurements of the environment that need to be interpreted in order to provide a clear picture of what is happening.

Depending on the configuration of the sensors, objects located within the VOI will generate signals at one or several sensors. These signals may be corrupted with noise or be completely spurious. According to the JDL model, the interpretation of these measurements in order to generate preliminary estimates of signals is the first level (Level 0) of data fusion. Often this level of fusion is performed within the sensor itself. One example is the requirement for a minimum signal threshold before reporting measurements, a process that attempts to retain signals that correspond to objects of interest and discard noise. Another example is the integration of radar signals during a sector scan.

Level 1 fusion involves a slightly higher assignment role, where signal estimates are combined to generate inferences about objects in the environment. In our example, signals

and signal history from multiple sources are combined in order to make hypotheses about the properties of objects in the environment. Properties may include position or other kinematical information, non-kinematical information such as Radar Cross Section (RCS), and a measure of confidence (probability) in these properties. Level 1 is responsible for associating sensor readings with hypothesized objects in the environment and maximizing the knowledge about these objects based on sensor measurements.

Level 2 fusion furthers the knowledge of the environment by considering the relationships between the objects detected. Level 1 information is used to infer the overall situational picture. Physical, organizational, informational, and/or perceptual relationships between entities that are important to the mission objectives are considered.

Level 3 is the highest perceptual level in the fusion process. Here the situation developed in Level 2 is analyzed for potential impact and other sensitive information. The goal is to provide the most relevant and up-to-date processed information to the decision maker. In the above example, Level 3 fusion would provide a description of all of the objects and aggregate entities detected in the VOI (Level 1) as well as predicted information about their kinematics and potential impact of the platform mission and operations. In essence, it is at this level that critical information for decision making is shaped.

Level 4 is labeled “Process Refinement” but is often referred to as the sensor management level. Level 4 involves planning and control of resources, but no direct interpretation of the information gathered by those resources. Essentially, Level 4 takes the situational/impact analysis from other levels to redirect and reassign sensor resources to best meet the platform’s operational objectives. A more detailed discussion of sensor management is given in Section 3.2.

3.1 Data fusion architecture

Data fusion can be performed over sensors distributed on several platforms although the process is more complex than for a single platform. Constraints due to inter-platform communication and platform navigation can significantly impede the fusion process. The difficulty arises mainly in deciding what information should be shared among platforms in the face of bandwidth-limited communication links. In such a multi-platform setting, each platform requires a local fusion process to be implemented, if anything, for self-preservation; however, mission planners desire information that takes into account the observations of all platforms involved in the mission. There are several possible approaches to this problem.

3.1.1 Centralized architecture

The simplest yet least practical way is to send all of the raw sensor data to a central location to perform data fusion (centralized approach). This approach relies heavily on inter-platform communications and in cases where this communication is bandwidth-limited, significant time delays between detection and assessment may result. As will be seen in subsequent sections, sensor management is also more difficult in this configuration, as com-

munication delays reduce the ability to react timely to a changing environment. The overall result is a reduction in the quality of the information gathered.

3.1.2 Distributed architecture

The extreme opposite of the centralized approach to data fusion is a fully distributed approach. Here the sensor data are fused aboard each platform independently and only the refined information is communicated to the central fusion node. This approach has the advantage of minimal reliance on communications but passes over the opportunity to combine individual sensor measurements from different platforms synergistically.

3.1.3 Hybrid architecture

The best compromise solution lies somewhere between these two options. In order to minimize reliance on communications, some data analysis must be performed aboard the individual platforms, but in order to maximize the benefits of the sensing resources, something more than the high-level information needs to be shared.

3.2 Sensor management

In the most general terms, sensor management, as part of Level 4 fusion, acts as an aid to the data fusion process by directing sensing resources in an intelligent fashion. Because the sensors cannot always meet all of the sensing requirements, the management system must decide which priorities to meet and which resources to allocate to that priorities. These decisions are influenced by the high-level analysis (from Level 2 and Level 3) of the situation and generally balance the long-term objectives with immediate concerns. In this sense, sensor management boils down to choosing between a number of sensing strategies based on the conditions of the moment. Typically, the problem of selecting a strategy only arises when the situation changes in some fundamental way, such as when a new target enters (or leaves) the VOI. Once the strategy is chosen, the management system ensures that it is implemented by issuing commands to the sensing resources.

Information gathered by the resources can undergo the same fusion process without any feedback to the sensors; however, by redirecting the sensors based on the fused data, better measurements can be generated, thereby improving future fused results. This process of data analysis and sensor redirection can be thought of as a feedback loop. Figure 7 illustrates the fusion process without sensor management (*i.e.*, open loop).

Normal operating procedures control the sensors and the data they collect is used in the fusion process to arrive at a high-level analysis of the evolving situation. There is no formal provision for adjusting the sensing resources to gain better measurements. This can be thought of as a purely open-loop sensing strategy.

In contrast, Figure 8 illustrates the fusion process where sensor management is used in a feedback sensing strategy. Here the outputs from the fusion process are used by sensor management to make adjustments to the operation modes of the sensors.

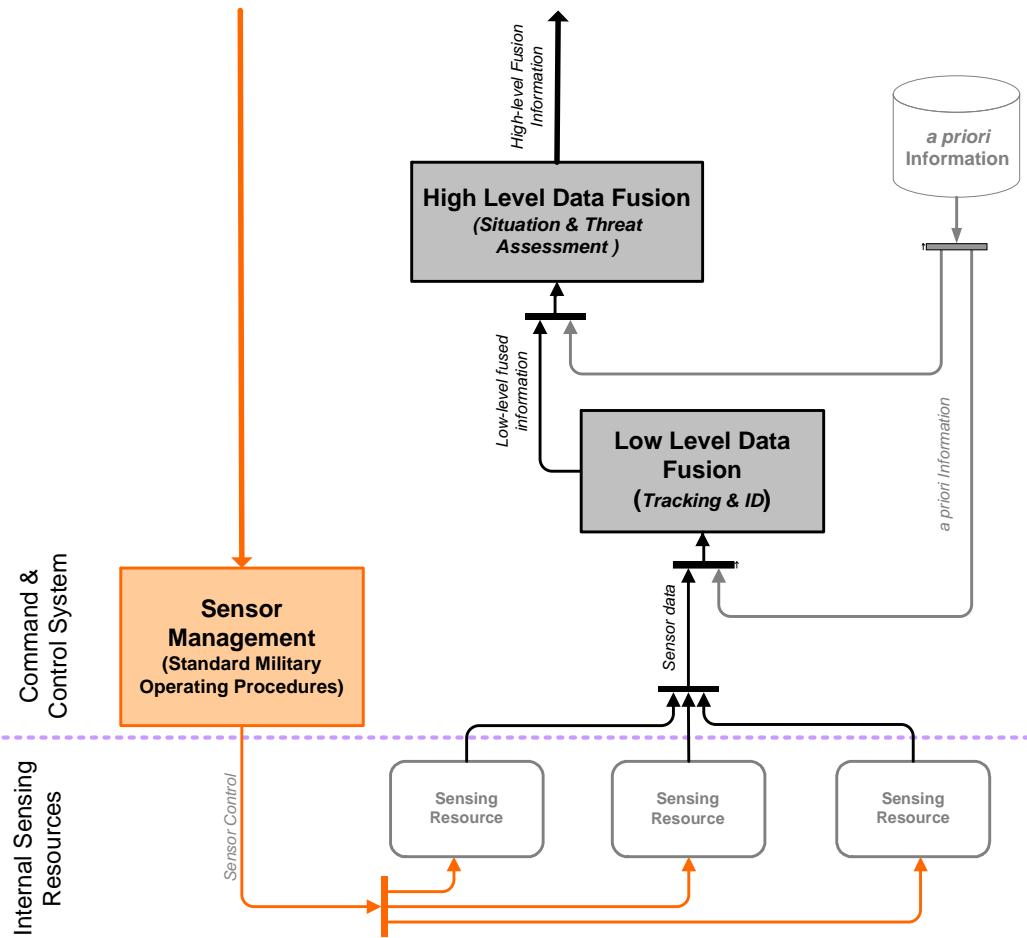


Figure 7: Open-loop fusion and sensing (no sensor management)

If we consider the typical JDL data flow between levels, illustrated in Figure 6, we can see that Level 4 receives input primarily from both Level 2 and 3 as well as directly from the resources (*i.e.*, all levels may provide input). In the above example, the object assessment (Level 1) would provide the kinematic descriptions of all of the objects in the environment, Level 2 would assess the organizational properties of these objects, while the impact assessment (Level 3) would indicate which objects are the most important to track (highest priority) and which ones require more or better information. Process refinement (Level 4) in this case would then consist in assigning and reassigning sensing resources based on this information and the overall mission objectives.

The next section briefly discusses some of the advantages of using sensor management in military target tracking applications.

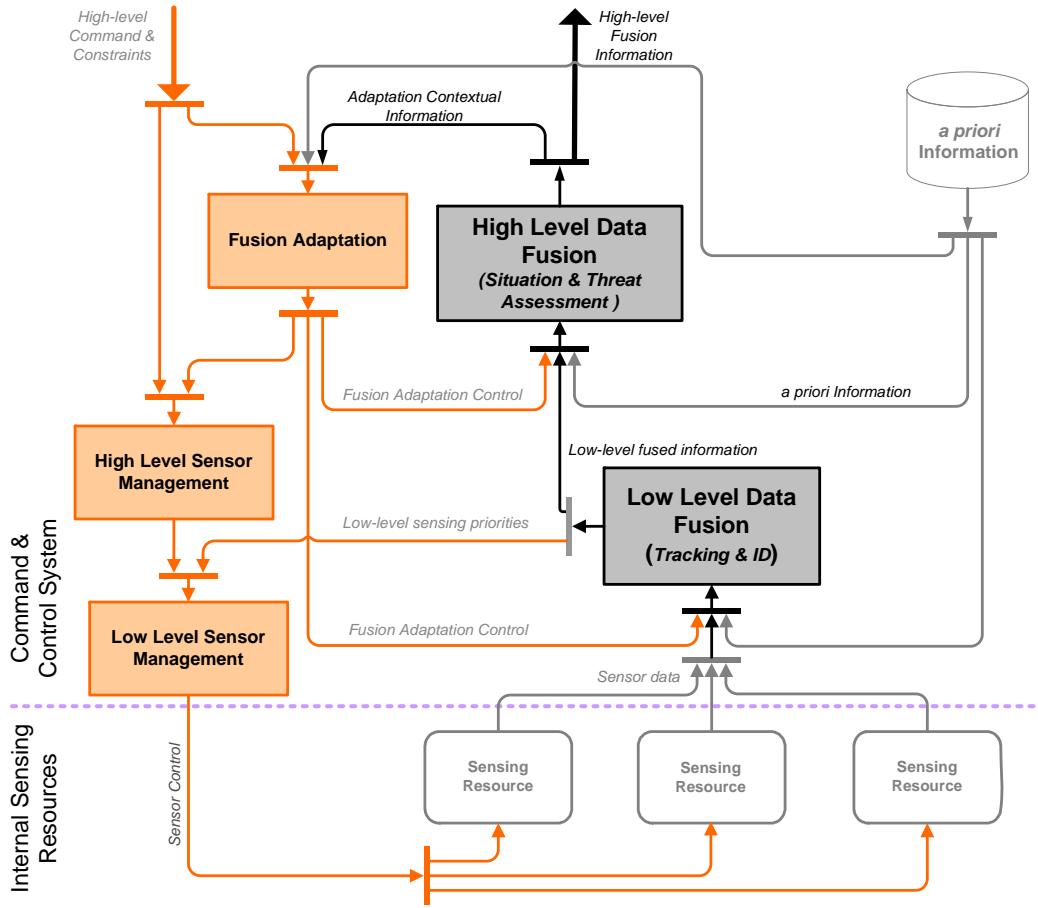


Figure 8: Closed-loop fusion and sensing (with sensor management)

3.3 Sensor management for target tracking

Target tracking in the military typically consists of a search phase and a tracking phase. Search is the use of sensing resources to detect new objects in a Volume Of Interest (VOI). Tracking is the use of sensing resources to get kinematical and other non-kinematical information about objects in the VOI. Search performance can be measured in terms of the percentage of the VOI that is searched (in a specified unit of time) by the sensing resources for new objects. Tracking performance is measured in terms of the time that a sensing resource devotes to gathering information about an object in the VOI and the performance of that sensor against the target.

Tracking and search are conflicting tasks in that sensors used for tracking are not available for search and vice versa. Search performance is improved by allocating more sensors to this task (in a multi-sensor setting), thereby searching more of the VOI in the same amount of time. Conversely, the more time sensors devote to measuring a single object, the less time they have for search. Sensor management must balance these two responsibilities in

order to achieve both sensing objectives.

Target tracking using the more advanced type sensor allows for the maximal flexibility in demonstrating the utility of sensor management. Without sensor management, radar sensors typically perform a bearing sweep at a constant rate, thus updating target tracks at regular intervals. Search is also limited by this sweep rate as particular regions cannot be searched more often than others. With sensor management, sector scanning can be directed to those regions most critical to the sensing objectives. This provides a more refined method of data gathering. Thus, high-level analysis of the evolving situation provides cues for control of the sensors. From a search perspective, for example, regions where new targets are expected can be swept more often. Similarly, with respect to tracking, targets of high priority can be revisited more often.

Target priority is determined by a high-level analysis of the evolving situation. With present technology, this analysis is done by humans with the assistance of computer algorithms. Targets can be assigned high priority if they are determined to be of significant threat. An incoming missile, for instance, would be much more significant than a friendly target traversing the same region. Threat level can be determined by kinematical cues such as approach rate, or non-kinematical cues such as target identity. In either case, it is imperative that the sensing resources attain sufficient track quality to deal with the threat as quickly as possible. Sensor management can be of significant help in this circumstance by reassigning resources to more critical tasks.

In the following, we illustrate the principles behind sensor management with respect to balancing search and tracking performance. Three management scenarios are discussed: a single sensor surveying one or many targets, co-located sensors on-board a single platform used against multiple targets, and a network of distributed sensors aboard multiple platforms. Target tracking in these scenarios will be used to demonstrate that closed-loop sensor management can improve sensing performance over an open-loop type of sensor management. Target tracking is used for illustrative purposes but the advantages of sensor management are not limited to this particular application.

3.3.1 Single sensor

The first scenario considered is that of a single sensor used against a single target. When no sensor management is used, the sensor performs a steady sweep at a fixed rate. This means that the VOI is searched at a constant rate. Likewise, once a target is located, its track is updated at this steady sweep rate.

When sensor management is employed, the relative priority of the target can be used to modify the update rate of the sensor. If the target is friendly, its priority would be low and sensor management would simply continue with a regular steady sweep. On the other hand, if the target was determined to be a threat, sensor management would abandon the search task and confine its sweep to a small region surrounding the target, or continue with the search sweeps but revisit the target more often. In either case, much better quality track information could be gathered in a shorter time, thereby improving tracking performance.

In this case, search performance is impacted negatively but the overall mission objectives (*i.e.*, self preservation aspect) are more successfully achieved.

The case of multiple targets against one sensor is similar to the one with a single target. Without sensor management, the sensor would revisit each target at the same rate. Sensor management provides for targets found to be of high priority (threat) to be visited more often than low priority ones. Thus, track information regarding threatening targets would be gathered more quickly than non-threatening ones.

The above cases illustrate the types of trade-off that sensor management can make to best achieve mission objectives. Analysis of the incoming data, combined with mission objectives, can be used to reconfigure the sensing resources in a dynamic fashion. In the above cases, it is the responsibility of sensor management to balance surveillance performance with tracking performance. Each aspect takes on a relative importance based on the changing conditions in the environment. Typically, when targets are friendly or not present at all, search takes on a greater importance. When hostile targets are present, search must be sacrificed in order to maintain tracks of sufficient quality for tactical response.

3.3.2 Co-located sensors

When multiple sensors are used, two main cases emerge as the search and tracking responsibilities can be addressed independently. In the first case, there are fewer targets than the sensors can track; thus, every target can be tracked sufficiently well for the mission objectives. In the second case, the targets overwhelm the sensing resources and sensor management must trade search performance for tracking (or vice versa).

Without sensor management, each sensor will scan the region at a constant rate and this is how search and tracking are generally traded off regardless of how many targets there are or how hostile they are. With sensor management, in the first case mentioned above, threatening targets can be tracked closely while friendly targets can be ignored, and the remaining sensing resources used for search. The particular breakdown of resources is a matter for the sensor management system and the high-level analysis of the situation.

In the second case, sensor management can choose to ignore the search task completely to focus on tracking hostile targets. The exact strategy would depend on the number of hostile targets in the volume of interest and those expected to arrive. In extreme cases, when a great many number of targets are present, only the most threatening targets might be tracked.

3.3.3 Distributed sensors

The multi-platform scenario provides the greatest opportunity for sensor management to improve sensing performance. In a military setting, sensor management is best implemented in a hierarchical fashion, where each platform (such as a frigate) manages its own sensing resources and the military command manages the platforms as though they were its own

resources. In this way, individual platforms can carry out independent missions and ensure self-preservation while cooperating in a broader observational effort.

Platforms can accept sensing tasks from the next highest level of military command and incorporate them into their own sensing objectives. Depending on the situation and the priority of the task, the platform sensor management decides which resources to allocate to which task. For example, a command to perform search in a particular region would be executed unless the resources were needed to respond to an immediate threat. In this case, the search objective is of lesser priority to the platform than that of self-preservation.

With no group level sensor management, each platform would track all of the targets in the region surrounding it. From a group-level C2 point of view this is a redundant use of sensing resources. Sensor management from the command level determines which platforms should track which targets, and which platforms should survey which regions.

The platforms themselves then take these commands and decide how and if they should implement them using their own resources. High-level analysis at the group and fleet level can provide for an additional and more complete assessment of the emerging situation. The information about high priority targets thus obtained can then be provided to the platforms themselves. Platforms could refine their sensing by maintaining close tracks on all high priority targets while still be privy to search information gathered from other platforms.

The above described scenarios show the benefits and need for sensor management. The next chapter discusses issues related to sensor management for each scenario.

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4 Issues in the management of tactical sensors

This section will discuss some of the issues that sensor management should address in a tactical surveillance situation. Also, some technologies potentially applicable to sensor management will be presented. As discussed in the previous section, sensor management closes the loop over the sensing resources, that is, based on the information gathered and fused dynamically, develops sensing options. The formulation of the sensor management problem assumes the existence of one or more of the following scenarios:

- Single sensor** – a multi-mode, multi-function, and/or agile single sensor;
- Co-located sensors** – a suite of multiple sensors on a common platform; and/or
- Distributed sensors** – a set of geographically distributed sensors/platforms.

As discussed below, these different situations define different classes of management problems.

4.1 Management of a single sensor

Management of a single sensor primarily involves scheduling and mode control. Scheduling for a single sensor is the designation of time segments during which the sensor is achieving a given task. This may require a mode control. Scheduling of a single sensor can be time or event driven depending on the type of sensor and the situation in which it is being used. Mode control for a given sensor is the set of actions necessary to alter the configurable parameters for that sensor.

4.1.1 Sensor scheduling

Scheduling is the designation of time segments to specific tasks or activities, the nature (and some cases the order) of which is defined during the planning⁶ stage. Scheduling is essentially an optimization problem that aims at generating a plan for the execution of required tasks in the most efficient way given limited resources. The allocation of resources to tasks (*i.e.* planning) and time scheduling for those resources are separate yet coupled processes.

Scheduling typically uses time as its base variable; tasks are expected to start at a specified time and to execute for a fixed time interval. State is used as a secondary constraint. In tactical surveillance, a sensing system could be tasked to monitor a sector of the Volume Of Interest (VOI) for a specified period of time and then reorient itself to monitor another sector. In this situation, the task is defined by the start time and the duration.

On the other hand, it might be more suitable to use the state of the system as the base variable and time as a secondary constraint to monitor duration, to avoid any undesirable

⁶Initially a goal is stated. From this goal a plan is developed in which a list of tasks and events that must occur is generated. To implement this plan, scheduling of time or events to task and allocation of resources to tasks is done.

time-dependent events. Such an approach is called discrete event scheduling. The surveillance system could be tasked to monitor a sector of the VOI until a contact is reported and a track established, at which point it may be asked to perform another task. This activity is not time-dependent but state-dependent. Therefore, the schedule cannot use time as the base variable.

Scheduling theories have been extensively researched since the early part of the 20th century in the fields of: project management, military logistics, manufacturing, construction, agriculture, and software (operating systems). The diversity of these fields indicates that scheduling is a body of research that stands on its own. Research teams have applied a host of advanced techniques to improve the performance of scheduling algorithms including:

Artificial intelligence – Constraint logic programming based on constraint satisfaction has been applied to the generation of optimal schedules, as in Cosytec's CHIP⁷ and the Ilog's Scheduler⁸.

Neural networks – Neural networks are applied to problems finding an optimal solution. Scheduling is an optimization problem so the neural network can generate an optimal schedule provided that it has been sufficiently trained. Researchers in business [4] and engineering [5] have developed neural network based scheduling tools.

Genetic algorithms – Genetic algorithms are excellent for searching large dimensional sets for a best solution and can be applied to scheduling as a tool to find valid and optimal solutions.

Fuzzy logic – Rule-based fuzzy logic can be incorporated into existing scheduling methods to provide optimal control of batch services [6].

It is often the case that researchers apply some hybrid scheme of the above algorithms to explore ways of improving stability and efficiency of the schedule and the generation process.

There are two basic scheduling techniques: deterministic and stochastic [7]. The application of deterministic scheduling practices to tactical surveillance is inappropriate for the most part because a good adversary is unlikely to be predictable enough to allow you to plan in advance all the tasks necessary to monitor them. Therefore, an adaptive scheduling system that is capable of handling stochastic events is required. The system must be able to adjust the surveillance schedule for a target that can arrive and depart from the VOI at any time, it must be able to cope with sensing resources that can go off-line or come on-line with no notice. The operating environment for tactical sensing is fluid; therefore, the scheduling system must be capable of generating an updated schedule as the situation demands. For instance, a sensor may be scheduled to survey a sector within the VOI for a specified time. However, the situation changes and three new targets arrive in an adjacent sector. Since these targets are characterized with a very high threat level, it is necessary to track them,

⁷http://www.cosytec.com/production_scheduling/constraint_programming_technology.htm

⁸<http://www.ilog.com/products/scheduler/>

so the schedule and allocations must be adjusted to meet this situation. Rigid plans and schedules are not appropriate for tactical sensing.

There are several approaches to scheduling that use either time and/or priority to make use of resources. To illustrate this, consider a simple sensing system that is capable of tracking only one target at a time. Borrowing from computer science, some scheduling approaches are:

Queue – First-in-first-out (FIFO), tasks are addressed in the order in which they are received. In this mode, the sensing system tracks the first target until it leaves the VOI. At this point, it will begin to track the target that arrived after the first one, provided it has not already left the VOI. This process is repeated until there are no targets remaining in the VOI. This method does not prioritize the targets to be tracked based on their threat level and will only address targets in the order in which they appear, one at a time. Therefore, queue-based approach is not appropriate for tactical sensor management.

Stack – Last-in-first-out (LIFO), tasks are addressed as they arrive. Tasks are suspended and placed on a stack when a new task is received. When the newly arrived task is completed then the task on the top of the stack is reactivated until completed or interrupted again. With this strategy, the sensing system will track the most recently arrived target until the next one arrives, no matter the priority. This is not appropriate for a tactical setting because it may force higher priority tasks into the stack while lower priority tasks are addressed. Another disadvantage of LIFO is that a task may be pushed down so far on the stack that it is possible that it will never be serviced.

Interrupt driven – If an active resource is allocated to a higher priority task, then the current activity is suspended until control of the resource is relinquished by the higher priority task. When a task is suspended, it can be placed on a stack or placed at the head of the queue while it is waiting its return. The consequences of interrupting a task can be significant and may have impacts on safety and operational functionality. For some tasks, it is more appropriate to terminate than to suspend them during mid-operation, while other tasks can only be interrupted at specific points in their process. With this strategy, the system will track the target of highest priority that is assigned based on the result of high-level analysis. Interrupt driven scheduling is appropriate for tactical sensor management.

Time-slice multi-tasking – A task is allocated a time slice that is proportional to its priority. The task priority is not fixed and can be altered up or down, depending on how the situation evolves. However, there is an upper limit to the number of tasks that can be handled at any given time, because if the time slices become too small then the system becomes so ineffective that no tasks are completed. With this strategy, the sensing system would track a given target in the VOI for a percentage of the time based on the assigned priority. The assigned target priority is subject to change based on target behavior and the arrival and departure of other targets. Each change in assigned priority forces the tracking schedule to be adjusted dynamically.

Because of its ability to adapt to the varying priorities of the targets, this method is viable for scheduling in tactical sensor management.

Round robin multitasking – Each task is serviced by the resource for a specified amount of time. At the end of each allocated time slice, the task is suspended, and placed at the tail of the service queue, while the next task is serviced. A task remains in the service queue until it is completed. With this strategy, the sensing system will track all targets in the VOI for an equal percentage of time. This method is adaptive in the sense that it can accommodate targets arriving and leaving up to a maximum number and has the advantage that it addresses all the available targets in the VOI. However, its disadvantage is that each target is treated equally, so it does not address priority levels. A friendly target is treated the same as a foe with a high threat level. As a result, this method is not appropriate for sensor management in military environment.

Among these methods, the interrupt method and the time-slice multitasking are the most appropriate for sensor management. These two methods allow for the unexpected arrival of new targets and can be adjusted based on the threat levels assigned to each target.

4.1.2 Mode control

Some tactical sensing systems have multiple modes of operation, which allows these systems to have a broader functionality than that of single mode systems. Changing between modes enables the performance to be tuned to meet a specific requirement. Having the flexibility to alter modes of operation does have a cost, often the gains made for one measure of performance come at the reduction of another. By managing the use of these modes, more effective information gathering can be achieved. Sensor management provides direction to the sensor system operator (human or computer) regarding the desired mode.

A simple scanning radar system has a number of parameters that can be adjusted to alter its performance. The three most significant ones are: the power transmission, the receiver's gain and the scanning rate. All influence the ability of a radar set to detect a target. The effective range of the radar system is proportional to the power transmitted and the receiver's sensitivity. Increasing the transmitted pulse length will increase the transmitted energy, thereby increasing the range of the sensor. At the same time, the longer pulse lowers the range resolution. The dwell is inversely proportional to the revisit/update rate of the radar. If the radar is scanning at a relatively high speed, then the revisit rate is high, which is beneficial for monitoring temporal changes in the spatial coordinates of the targets. However, the reduced dwell will lower the quality of the observation, which may require many repeat observations to establish the same level of confidence in the target track.

Moreover, the radar has two modes, a short and a long range. If a target is being tracked in the short range mode and it is approaching the range limit, then to maintain track, it may be prudent to change mode to the long range mode. The sensor management system

must decide, based on the rules that govern the decision-making process, if a mode change is advantageous at this time or if maintaining the current mode is more appropriate.

Therefore, compromises must be reached between range and resolution and between the contact data quality and the update rate. This is partially addressed by the equipment designers by placing limits on how much a parameter can be adjusted. The remaining responsibility lies with the sensor management system that must select optimal parameters.

The consequences of changing mode can include:

The sensor may become blind during the transition – During a mode change, a sensor may not be able to provide any data for a period of time. In a high threat situation, it may be better not to change the mode because the loss of current data, albeit not the best possible data, may have greater consequences than the gains made by changing the mode. Priorities provided to the sensor management system would help to define the best compromise action.

Power consumption may increase or decrease – In situations with a limited power budget, changes in power consumption may introduce a conflict with other resources. For example, in an UAV, it may not be possible to operate a radar system in a high-power mode and operate other sensors simultaneously. Therefore, if it is determined that the radar is to be used in the high-power mode then the other sensors must be deactivated. Sensor management must consider the impact of changes in power consumption when allocating another mode of a sensor.

Change the volume or format of data stream – In many digital cameras, it is possible to change the image resolution and occasionally the file format. Should the image resolution be increased, the volume of data is increased. The benefit is that the image quality is increased. However, the cost is that transmitting the images requires more bandwidth and more storage space is required. If the image file format is changed, it may require that the image be viewed using different software. Sensor management must consider how the data being collected are to be used and by whom. If the requirement is for a basic image, then there is no reason to have the largest possible image resolution, etc.

4.1.3 Countermeasures

Electronic Warfare (EW) comprises Electronic Attack (EA) and Electronic Protection (EP). An adversary can make use of his EA to attempt to confuse tactical sensing and lower the data quality, thereby lowering the confidence levels in those data. The careful use of EP methods can assist in allowing operations to proceed with surveillance data of sufficient quality.

The most basic strategy of EW is to make own assets more difficult to be detected, identified, and tracked by enemy sensors. This is achieved through the minimization of all forms of radiated energy from own active sensing and communications systems. When the use of active sensors and communications transmission is necessary, it should be done using a

pseudo-random schedule that will make it difficult to predict the next pending transmission. Sensor management contributes to minimizing the radiated energy emitted from a platform by using active sensing systems only when necessary and by transmitting data streams to other platforms only when required for overall situation analysis. The priorities that define when it is appropriate to use a particular active sensing system are formulated as constraints in the sensor management decision making process.

For example, using lower power settings on search radars reduces the range but also decreases the emitted energy, which in turn lowers the electromagnetic signature and reduces the probability of being detected. Using passive sensors also lowers considerably the electromagnetic/acoustic signature. Using passive sensors and minimizing the use of active sensing systems will limit the amount of radiated energy that can be used by an adversary to detect one's presence and possibly location. However, this must be weighed against the use of active sensing systems that may be necessary for detecting one's adversary and own weapons' fire control. Following the assigned priorities, sensor management will determine the best balance between avoiding detection and ensuring that enemy platforms do not enter the VOI without being detected, identified and tracked.

Sensor management should also be kept aware of the use of EA because certain EA techniques will interfere with certain tactical sensors. For instance, the use of a radar noise jammer may emit energy that will impact ESM or search radars. Sensor management can adapt sensor scheduling and operations mode to take into consideration the EA being used. Also, when deemed necessary, sensor management can make recommendation to change or cancel the current EA techniques.

Countermeasures can also be physical decoys meant to appear as the probable target to the sensor that is tracking it. These decoys can be passive, such as the chaff that is intended to create a large radar signature to confuse radar guided missiles. They can also be active, such as the towed AN/SLQ 25A Nixie carried aboard the Halifax Class frigates, which creates a false acoustic signature to provide a false target for the torpedoes. Guided by the situation analysis process, sensor management may be to distinguish between the decoy and the real target. Decoys (both friendly and enemy) must be handled carefully as to ensure the protection of tactical sensors and to avoid that data be misinterpreted.

4.2 Management of co-located sensors

The goal of managing a suite of sensors is to utilize more than one sensing resource to gather the best information about the environment, continually, and with minimal time delay. When multiple sensors are utilized on a single platform, control and coordination is complicated due to the differing data types, time scales, reliability, and ranges and resolutions. Sensors may also interfere with one another during operation and may be disparate or overlapping in their sensing ranges and modes. All of these factors need to be considered in real time in order to achieve the sensing objectives.

This section discusses the challenges of managing a set of such sensors co-located on the same platform. Note that the problems and challenges discussed in Section 4.1 concerning

single sensor management still apply here. Nevertheless, only challenges specific to multi-sensor configuration will be addressed in this section.

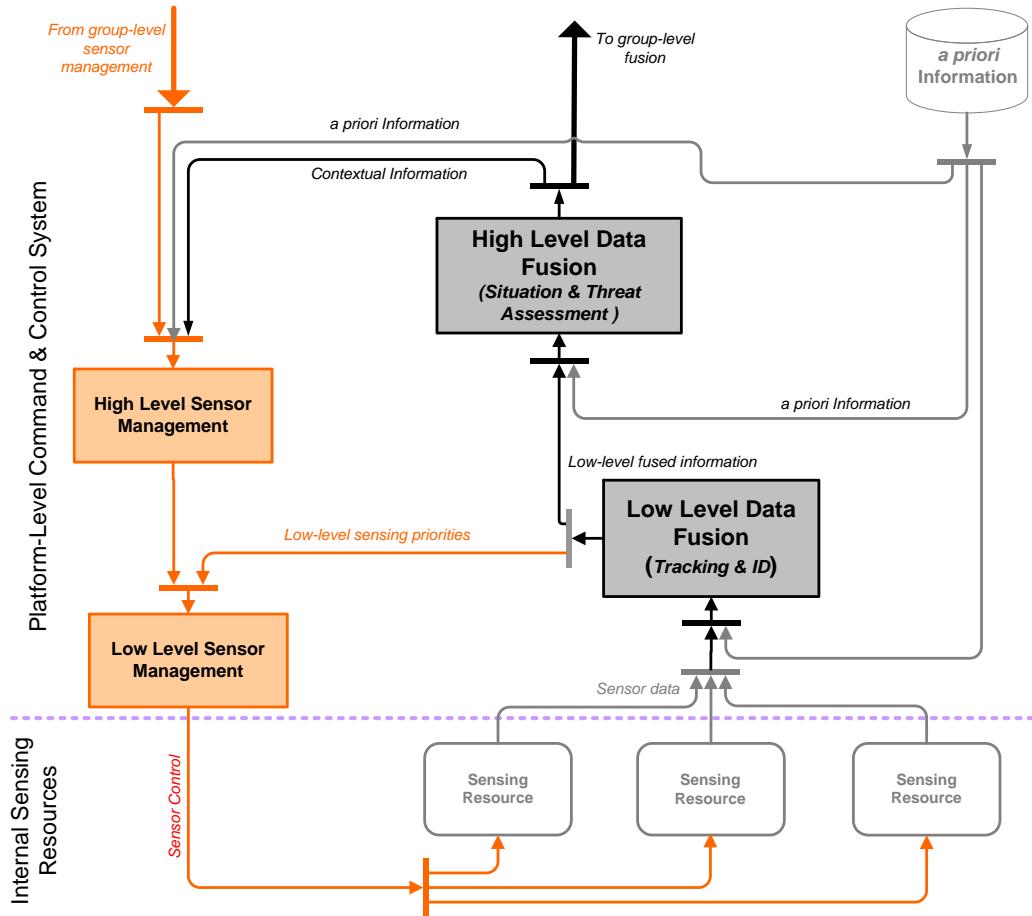


Figure 9: Management of co-located (single platform) sensors

4.2.1 Mode control

Multiple sensors provide an opportunity for fine-tuning the data collection exercise through mode control. Typically, sensor modes affect the characteristics of the data collected and as such, affect the quality of the information gathered by the suite of sensors as a whole. Sensor management can maximize the advantage gained through the control of individual sensor modes. As an example, consider the case of tracking a single target with two mode-configurable sensors. One sensor can be used to perform broad sweeps of the area of interest to approximately locate the target quickly, while the other sensor can be operated in a narrow-scan mode to obtain a precise fix on the target. This method provides better quality measurements in a shorter time than operating the two sensors in the same mode simultaneously.

The presence of multi-mode sensors complicates the job of the sensor management system.

The system must keep track of the various modes available for each sensor and the relative characteristics of each mode. In addition, various sensor/mode combinations may be conflicting and may have to be avoided. When addressing sensing requirements, all of these characteristics must be considered before a mode is selected.

4.2.2 Sensor/task pairing

Sensing resources must be controlled if they are to gather information that is of practical use. One of the main issues that the sensor management system must address is to determine which sensing resource to use at any given time and how to use it to best achieve the sensing objectives. By breaking down the sensing objectives into a series of tasks, the sensor management system needs only to determine the most suitable resource to allocate to each task. This is the sensor/task pairing or allocation problem [8].

Pairing is a dynamic decision process that matches sensing priorities with sensing resources. Resources can be assigned based on current and predicted needs; however, not all sensing objectives can necessarily be met simultaneously. The sensor management system must generate alternatives and make the best choice for each given situation. In the target tracking example, the competing priorities are firstly to track as closely as possible the targets of interest, and secondly to search as much of the Volume Of Interest (VOI) as possible (for new targets). Given a limited set of sensors, the best quality track can be obtained by allocating all of the sensors to this task. However, the search task would then be neglected. A better solution is to allocate just enough sensors to satisfy the tracking requirement, while using the remainder for the searching task. The sensor management system must decide which sensors to assign to each task in order to optimize the overall sensing objectives.

Generating alternatives and choosing between them is a complex task that can be addressed in a number of ways. Generating alternatives is based on a high-level analysis of the situation and knowledge of the current sensor capabilities. The high-level analysis provides information regarding the threat level or other target priorities, predicted developments in the near future, and the current situational picture. These are all included in the normal fusion process. Knowledge of current sensor capabilities is not part of the fusion process and, therefore, a different supporting architecture is required to convey this information to the sensor management system. The latter needs information such as the operational status and the current level of utilization of sensors to generate sensing strategies.

Once all of the information is available, sensor management must determine which resource will be allocated to which task. There are a number of different approaches to this problem, but all of them rely on some form of metric(s) or performance evaluation(s). Generally speaking, a number of possible solutions can be generated and with the aid of a metric, the optimal one selected. The difficulty is the design of a metric that can balance all of the competing concerns.

4.2.3 Sensor cooperation: cueing and handoff

The sensor management system determines which sensor will be assigned to which sensing task. However, situations may occur in which a single sensor cannot fully complete the task and another sensor needs to compensate. In target tracking for instance, a tracked object may move out of the sensing range of the sensor allocated to track it. Another example may be that the information quality delivered by a sensor may not be sufficient to meet the sensing objectives. In these cases, use of additional sensing resources can overcome the problems. It is the role of the sensor management system to facilitate the cooperation between several resources. Two forms of cooperation can be identified; cueing and handoff [8].

Cueing – is the process of using information gathered by one sensor to direct another sensor towards the same target or event (Figure 10). Cueing is a sensor management responsibility but it can be implemented in a number of ways. In target tracking for instance, track information derived from a series of sensor measurements may be used to cue a new sensor to an object; this is track-level cueing. Another means of facilitating cueing is to use lower level sensor detections from one sensor to direct another sensor to the same object. This is contact-level cueing.

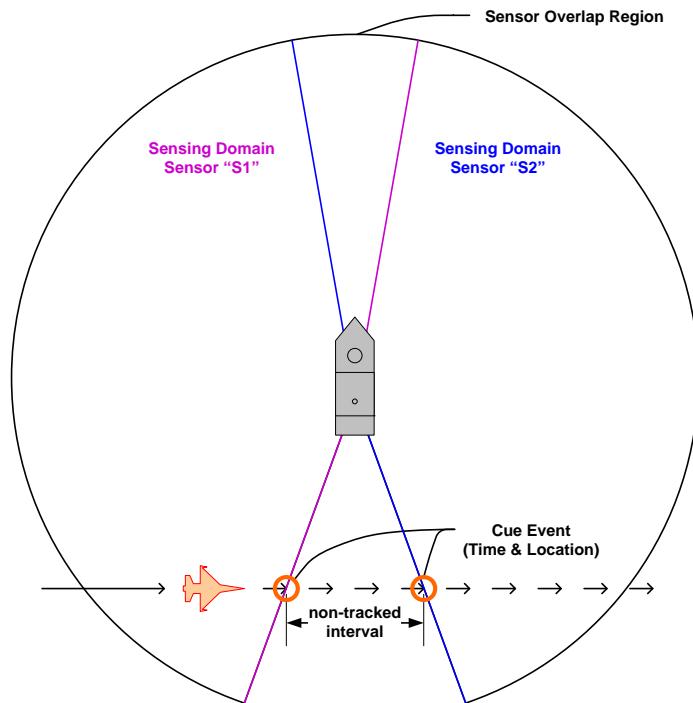


Figure 10: Cueing using co-located sensors

Handoff – is the transferring of task responsibility from one sensor to another. Handoff occurs when one sensor has cued a second sensor and is then removed from the sensing task (Figure 11). Handoff can help improve the response time and performance of

a cued sensor by using information gathered by the cueing sensor to give it a running start. In target tracking, for example, track-level cueing can significantly reduce the response time of the cued sensor by providing an expected location for the target. In addition, track quality is largely preserved, and track continuity can be maintained, should the tracked object pass out of the coverage (spatial/temporal) range of the cueing sensor.

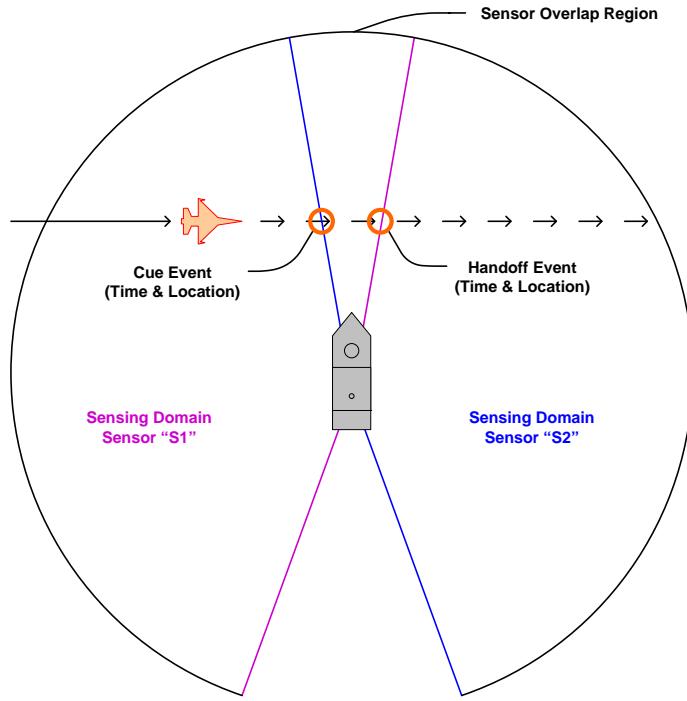


Figure 11: Handoff using co-located sensors

Cueing and handoff are part of the sensor management responsibilities. In order to compensate for sensor activation times (*i.e.*, pointing time, mode selection, etc.), the system may need to anticipate when cueing and/or handoff will be required. The management system needs to know the boundaries within which each sensor can operate and how close each allocated sensor is to those boundaries. Given this requirement, it is clear that this information needs to be communicated from the individual sensors to the management system through some communications architecture.

4.2.4 Coordination: conflict resolving

Coordination of sensors, *i.e.* allocation and control of sensors in a manner that avoids or resolves conflict, is the responsibility of the sensor management system. In the case of multiple sensors on board a single platform, the sensor management system should be aware of any potential conflicts that may arise in the operation of sensors and use this information to prevent possible conflicts. In target tracking for instance, active and passive radars cannot be operated simultaneously. This type of conflict can be planned for in

advance and the sensor management system does not require additional information to avoid this conflict while in operation.

The fact that co-located (on same platform) sensors share resources such as power and communication networks can lead to a conflict that may arise only during operation. For example, when a sensor-supporting platform has a tight power budget (*e.g.*, UAV), it is imperative that the sensor management system maintain enough power to operate the platform and the sensors aboard it. The only way for this type of conflict to be avoided is by acquiring information about the resources aboard the platform, in this case, power.

4.2.5 Sensors similarity

The sensors suite can be composed of multiple identical sensors, unique specialized sensors, or combinations of both. Suites of identical sensors may be simpler to manage (see discussion below) although sensing objectives are generally better met by a suite of heterogeneous sensors. In this section, we review and compare aspects of homogenous (composed of similar) versus heterogeneous (composed of dissimilar) sensor suites.

4.2.5.1 Interchangeability

Sensors typically have some overlap in their sensing capabilities. This provides a level of redundancy that can make the surveillance system more robust to single sensor failures. When all of the sensors are identical, any sensor can be used in place of any other sensor, provided they are configured in a way that allows it. For example, two shipboard radar systems can be used interchangeably if they are identical in specifications and can be directed (pointed) over the same sensing region. Limitations such as the physical location of the sensors may preclude them from pointing to the same region.

It is the role of the management system to substitute the use of one sensor for another when the situation arises. Thus it is important that the management system know which sensors can be interchanged and their degree of interchangeability. When the sensors are not identical, this issue becomes more complex. In addition to physical limitations, the differing types of data collected as well as the different time scales in which these data are reported affect interchangeability. In some instances, the function of the original sensor cannot be fully replicated by the other sensors. This situation requires inter-sensor cooperation to complete the sensing objectives.

The main benefit of managing interchangeability is the robustness it adds to the surveillance system. Not only does it allow to compensate for the individual sensors' failures, but it allows for the efficient substitution of allocated sensors amongst tasks in order to maximize the sensing objectives.

4.2.5.2 Complementary sensors

A suite of heterogeneous sensors is generally established to gather information in numerous forms. In a suite of homogeneous sensors, the data from one sensor can be easily improved

or complemented through the use of other sensors to focus on the same phenomenon. With heterogeneous sensors, different information is gathered from various sensors and this can lead to a better understanding of the environment as this information is fused. In target tracking, for example, a long-range sensor can provide the approximate location of a target and this information can be refined using a shorter-range yet more accurate sensor.

Sensors may not always be complementary, such as above-water sensors and underwater sensors on board a frigate. These sensors look at mutually exclusive parts of the environment. Using a underwater sensor provides no new information about strictly airborne targets, thus, with respect to this particular sensing task these sensors are not complementary. Whether sensors are complementary or not is situation-dependent and it is the role of the sensor management system to determine when combined use of sensors is advantageous. For example, under and above water sensors are complementary when the target is moving between these regions (such as a submarine launched sea-skimmer missile). Sensor management needs to be aware of the capabilities of the sensing resources and to be able to make situation-dependent decisions.

4.2.5.3 Time delays

Sensor readings are not instantaneous and may be discontinuous. In addition, different sensor types may report data at different time intervals. In a suite of identical sensors, the timescales of the sensors are all the same, which makes sensor management much less complex. When the sensors are reporting data at a number of differing time scales, sensor management must take into account the differing characteristics of each sensor.

Time scale differences can occur due to a number of reasons. Firstly, sensors may gather information at different rates. For example, different radars may have different scanning speeds and therefore produce target information at different intervals. Another source of time delay is due to the control of the sensors. Activation times, mode transition, pointing operations can all be sources of difference in the response time of the sensors.

The sensor management system must take into account the varying time delays when allocating sensors. This information is available beforehand and does not impact the communications that are required to support sensor management on a single platform.

4.3 Management of distributed sensors

Distributed surveillance involves the management of networks of sensors that are distributed across two or more platforms (Figure 12). This will typically involve (especially in military settings) a number of platforms (a group), as well as a group-level Command and Control (C^2). C^2 may be on one of the platforms in the group or it may be a separate entity. In either case, group-level sensor management is conducted from the C^2 location and it needs to address not only the problems exposed in Sections 4.1 and 4.2, but also new challenges that are specific to the distributed nature of the configuration. This section discusses those challenges.

Generally, communication amongst platforms is significantly more cumbersome than within the platforms themselves. In addition, the physical locations of the platforms can change over time, changing the configuration of the sensor network (*i.e.*, relative position of sensors). As a result, the group-level sensor management is concerned with both sensor control and platform navigation.

It should be noted that, in military settings, platform navigation may or may not be controlled directly by the sensor management, depending on the particular platforms. Smaller platforms such as Unmanned Aerial Vehicles (UAV) typically rely on direct control from the platform from which they were launched, while frigates are responsible for their own navigation and self-preservation.

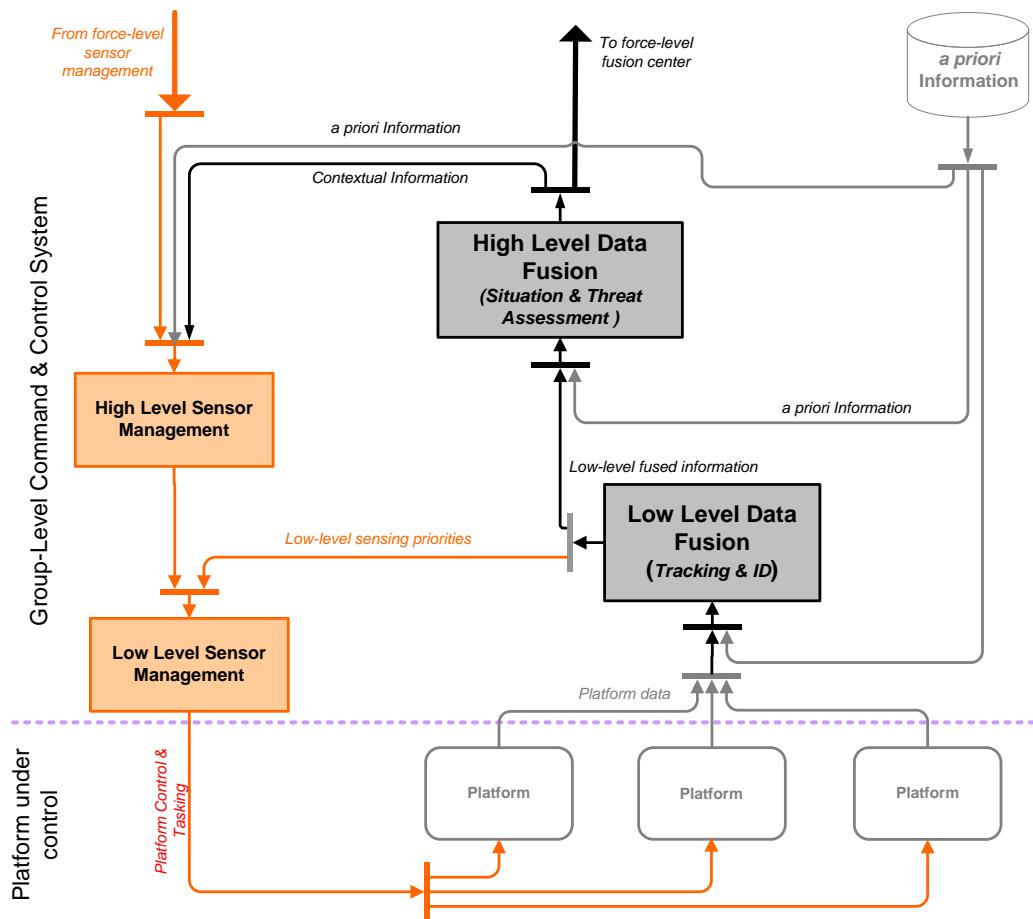


Figure 12: Management of distributed (onboard a group of platforms) sensors

Because inter-platform communication is generally limited and individual platforms operate under their own mission plans, fusing data from sensors across platforms is significantly different than in the intra-platform case. Fusion of low-level data (*i.e.*, raw measurements) across platforms is impractical because of bandwidth limitations and time delays attributed to inter-platform communication. As a result, it makes more sense to perform local multi-

sensor data fusion aboard each platform and then transmit this fused information to the group-level C². The latter can then combine it with data arriving from other platforms to gain a better picture of the environment than can be provided by any platform alone.

In target tracking for instance, sensor measurements from multiple sensors can be fused at the platform level (*e.g.*, aboard a frigate) to generate track information, but generating track information from sensor measurements on different platforms is not practical due to the time delays introduced by inter-platform communication. A better approach is to allow each platform to generate track-level data separately and then transmit this information to the group-level C² for further fusion processing. This approach reduces reliance on the communication subsystem, as less actual data need to be transmitted.

This fusion structure impacts on sensor management especially at the group-level. Sensor management at this level cannot directly control or access platform-level sensing resources; therefore it cannot allocate sensors to tasks directly. Group-level sensor management must instead allocate higher-level tasks to individual platforms. In target tracking for instance, sensor management may specify which platform should track which target, thereby avoiding duplication of tracking efforts aboard multiple platforms. The sensor management systems controlling individual platform resources would determine how to best perform the tracking tasks allocated to them.

4.3.1 Platform/task pairing

The resource/task paring problem in a multi-platform group is significantly different from the one aboard a single platform. Rather than allocating sensors to tasks, the group-level sensor management allocates tasks to platforms. Allocation of sensors to tasks remains the responsibility of the platform-level sensor management (see sub-section 4.2.2).

As an example, consider target tracking with two multi-sensor platforms and a group-level sensor management. New targets entering the area of interest require sensors to be assigned to track them. At the platform level, individual platforms are capable of assessing target priorities and managing their own sensors to independently track these objects. This information can then be fused by the group-level C² to provide a more detailed picture of events in the area of interest.

The scenario above describes a closed-loop sensor management approach within each of the platforms but an open-loop approach at the group-level (Figure 13). In the above case, the group-level C² does not use high-level assessments of the situation to adjust the sensing resources; rather it relies on the individual platforms to deliver appropriate information and simply fuses the result.

Closing this sensing loop amongst platforms provides advantages comparable to the advantages of closing the loop within a single platform. Group-level sensor management can address group-level sensing objectives and make more efficient use of the sensing resources. In the open-loop example, each platform would track all of the targets independently, which from the group-level point of view is a redundant use of sensing resources. Sensor man-

agement directed from the group-level can divide the information gathering responsibilities between platforms. In the above example, one solution would be to assign half of the tracking responsibilities to one platform and the other half to the second. This strategy reduces the overall burden on the sensing resources and therefore increases the tracking capacity of the group as a whole.

Figure 14 illustrates how group-level closed-loop sensor management can be implemented. Individual platforms are seen as resources to the group-level sensor management. The data reported by the individual platforms is combined and a high-level assessment of the situation is performed. Based on this assessment, the group-level sensor management decides which tasks to allocate to which platforms and transmits this information to the platforms. The platforms integrate these allocated tasks into their own mission objectives, and these objectives are then used to manage their own sensing resources.

In this typically military type of application, it can be noted that sensor management is hierarchical and recursive. The hierarchical structure arises because of the typical military command structure. The recursive element can be noticed in Figures 13 and 14. At the platform level, sensor management treats sensors as resources and the sensor management loop allocates these resources to meet sensing objectives. At the group-level, a similar process occurs, only here the input resources are individual platforms and the sensor management system allocates tasks to platforms. This recursive structure can be expanded to include inter-group management such as occurs when task-forces or multi-national coalitions are employed.

An important implication of this approach to group-level sensor management is the need for platform capability/status to be communicated to group-level C². In addition to sensor data, information such as current resource utilization, configuration, and location must be transmitted in order for sensor management to make the best decisions. Thus, inter-platform sensor management relies to a great extent on inter-platform communications.

4.3.2 Management architecture

Group-level sensor management provides for the fulfillment of the sensing objectives of the group. However, these objectives may conflict with the objectives of the individual platforms. For example, from a group perspective, it may be advantageous to use one platform to detect half of the targets of interest and another platform to track the other half. This strategy leaves the individual platforms partially blind to the occurrences in the Volume Of Interest (VOI), a situation that is unlikely to be tolerated in military settings. In practice, it is necessary for the individual platforms to balance the sensing requests made by the group-level sensor management with the objectives and concerns of the platform itself. For instance, frigates are responsible for their own self-preservation during military operations, thus sensors engaged in this objective should not be allocated to a lesser priority task issued by the group-level C². For example, if an incoming missile is a significant threat to a frigate, then sensing resources allocated to track it should not be reassigned to track a friendly target, even if requested by the group-level sensor management.

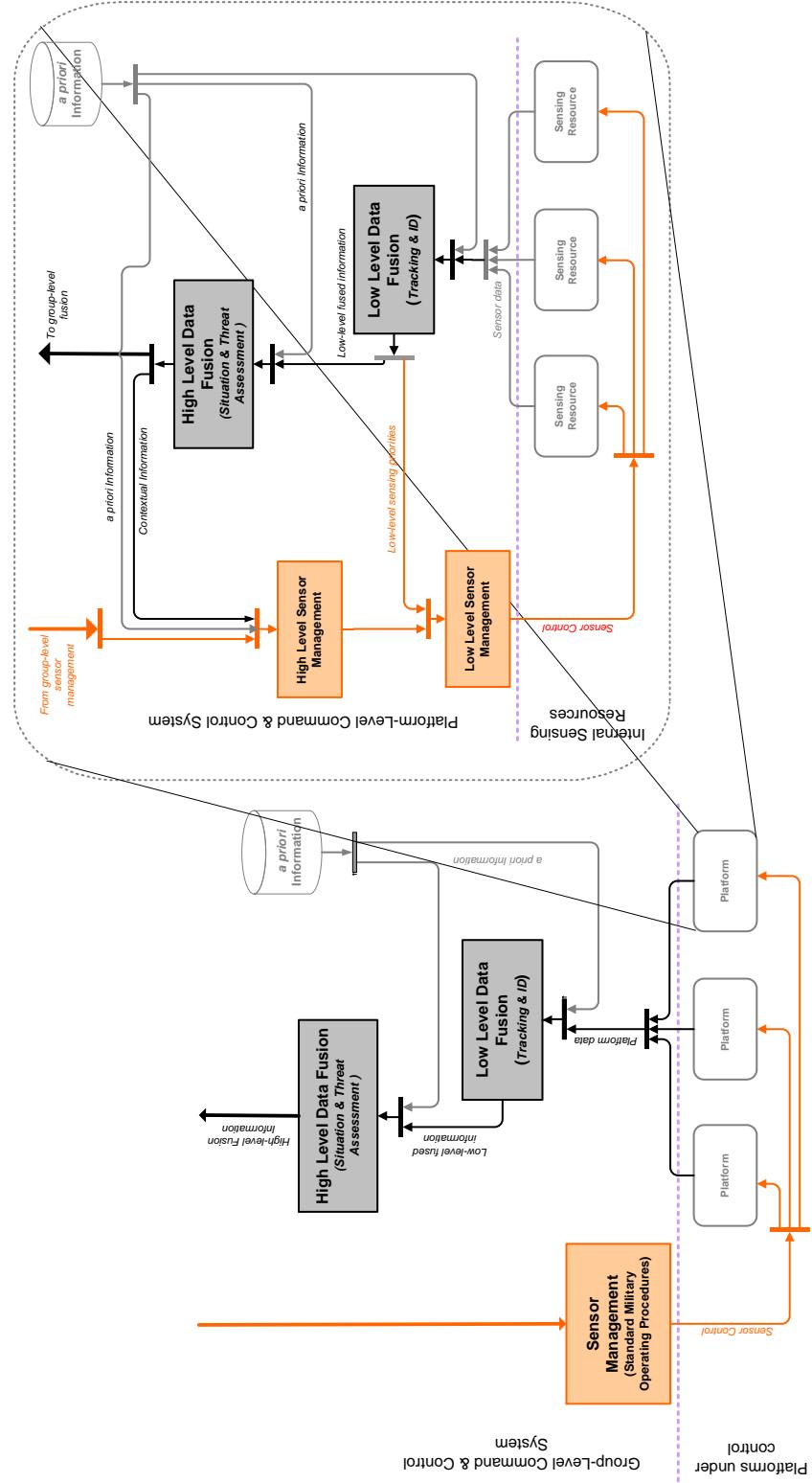


Figure 13: Open-loop group-level sensor management combined with closed-loop platform-level sensor management

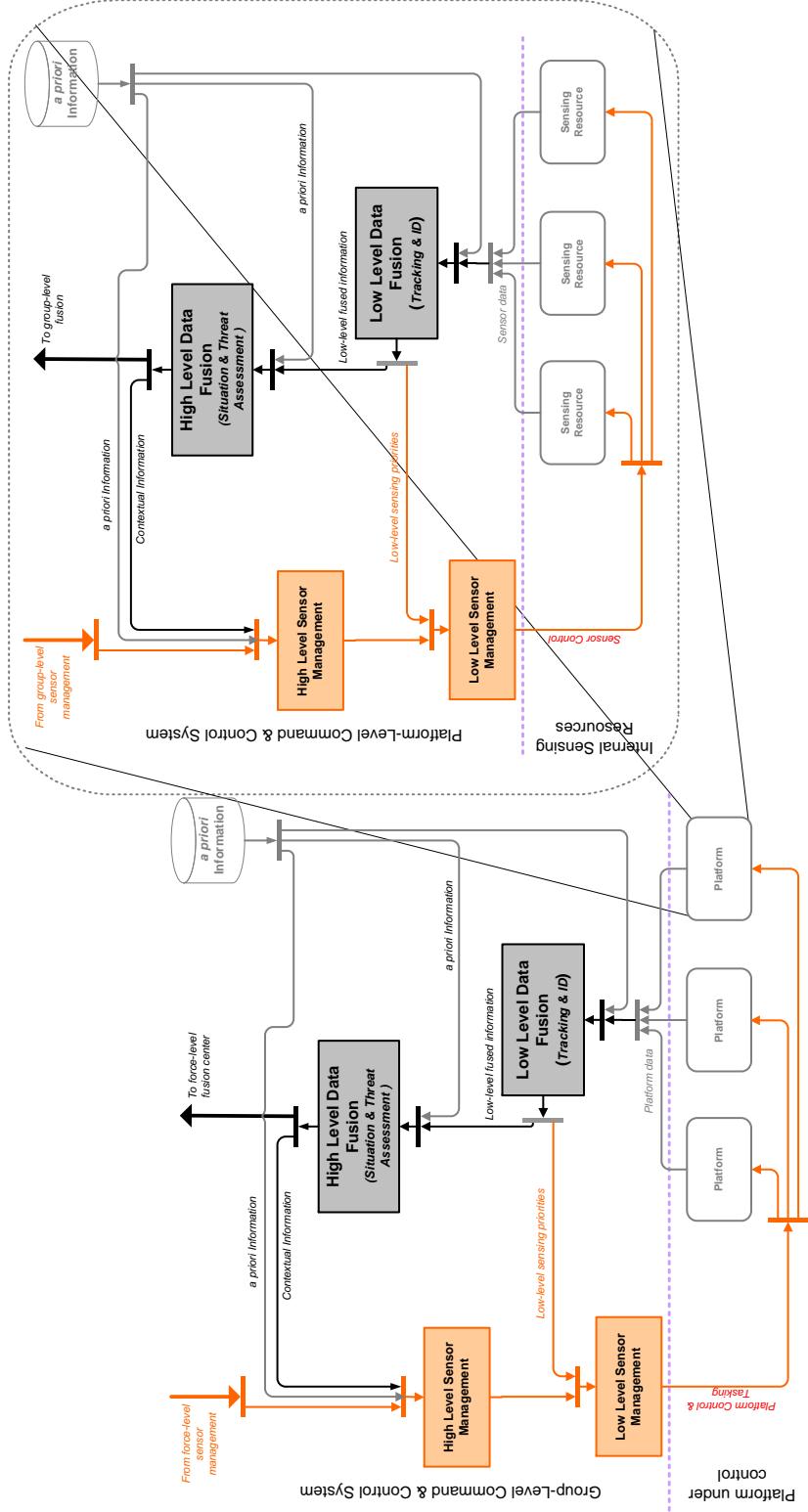


Figure 14: Closed-loop group-level sensor management combined with closed-loop platform-level sensor management

The sensor management strategy employed across the group must take into account the objectives of the individual platforms. This can be implemented in two ways. One way is to keep the group-level sensor management informed of the platforms' current sensing objectives and allocating tasks based on a compromise between the group objectives and the platforms' objectives. This is called the centralized approach to sensor management since all of the decisions are made in one centralized location. An alternate method to this is where the platforms themselves participate in the decision-making process. In this distributed approach, the group-level sensor management only decides what sensing responsibilities (tasks) to allocate to which platforms, but does not specify how the platform should address them. The platforms themselves (platform-level sensor management) decide how to complete these tasks using their own sensing resources.

The distributed method has the advantage of not requiring sensing objectives to be communicated to the group-level C², and makes the decision process at the group-level less complex. In addition, the individual platforms do not have to rely on decisions made from a remote location and can respond more quickly to threats.

4.3.3 Communication constraints

The management of sensors across multiple platforms relies heavily on wireless communication means, such as tactical Link-11. The wireless nature of these communication means imposes several constraints on the sensor management system. These constraints are discussed in this section.

4.3.3.1 Bandwidth limitation

All communication is limited by bandwidth. Within a single platform, bandwidth constraints are often not an issue. However, inter-platform communication, through Link-11 for instance, can be quite limited in bandwidth with respect to the data produced by sensors. This bottleneck affects sensor management by creating time delays in the reception of information from platforms and in the sending of task commands to platforms.

The sensor management system should be aware of any limitations in bandwidth and account for this in selecting sensing strategies. Bandwidth limits not only the sensory data, but also the platforms' status data, limiting the ability to react quickly to changes in the environment.

4.3.3.2 Time delays

Management of sensors across platforms is limited primarily by communication delays. Communications among platforms with limited bandwidth result in delays in data transfer. Such delays may arise directly as a result of the time it takes to transfer sufficient data, or as a result of pre-processing/compression performed before transfer. Time delays may also be introduced as a result of scheduling, where higher priority communication (*e.g.*, weapons systems) supplants sensor data. Furthermore, delays can arise as a result of detectability concerns, where communications are restricted or scheduled.

4.3.3.3 Reliability

Inter-platform communications, wireless in nature, are subject to environmental effects that may reduce bandwidth or cut communications completely. Communications may also be affected temporarily by obstacles in the environment, or be actively disrupted by hostile elements. In addition, detectability concerns may limit or cut communications altogether. These elements need to be considered and planned for in the sensor management strategy.

4.3.3.4 Communication costs

Communication costs are directly related to power consumption. On smaller power-limited platforms, this may become a driving issue for sensor management. Sensor management strategies must balance the working lifetime of the platform with communication requirements. Power conservation can be managed through localized processing that reduces communication requirements. Minimizing the allocation of power-limited platform resources is another strategy available to sensor management.

4.3.4 Platform navigation

An additional difficulty in sensor management is the movement of the platforms themselves. Depending on the platform, sensor management may be responsible for controlling navigation, or simply requesting navigational changes. In a frigate, for example, military personnel control navigation but a UAV's navigation may be controlled by sensor management.

Apart from the navigational responsibilities, the relative movement of the platforms may change the sensory capabilities of the group. For example, a sensor's view of a target may become occluded by another platform moving in the way. Also, platforms may move out of communications range or new ones may move into the range. Sensor management must be able to address such occurrences.

Navigational information is of significant importance to the sensor management strategy at both the group level and the platform level. This information can be determined from navigational sensors aboard each platform or from sensors located elsewhere in the network. The allocation of sensors requires that the current position of platforms in the sensor network be known. Platform navigation may temporarily limit sensor resources from being utilized, thus it is important for the management system to plan for this situation when suggesting navigational commands and to be able to respond to unforeseen platform movements.

A significant complication in the management of sensors across a network is the reconfigurability of the network. Movements of platforms may change the relative positions of the sensors and thereby change the capabilities of the sensing resources. The management systems must be able to adjust to these changes in a dynamic fashion in order to best meet the sensing objectives.

4.3.5 Coordination: conflict resolution

Conflicts between platforms can arise as a result of navigation, communications and sensor utilization. Group-level sensor management must address these conflicts during operation to achieve the overall mission goals.

Navigation can cause conflicts in two ways. The first and most critical is the possibility of platform collision due to sensor management control of navigation. This is easily avoided when up-to-date navigational information is available, but in many cases, communication constraints can delay this information. As a result, sensor management may have to anticipate or predict the locations of platforms to avoid collisions. A second navigational conflict arises when one platform blocks or occludes sensors on another platform. This is a similar problem to the collision avoidance issue but also depends on which sensors are currently being utilized.

Communications between platforms can interfere with one another if not properly coordinated. This is not necessarily a sensor management problem and may be addressed by the overall system design. In situations where the inter-platform communication channels are limited, scheduling of inter-platform communications falls under the purview of sensor management. Conflict resolution in this case may impact the overall sensing performance as communication is limited and time delays are introduced. The sensor management system has to decide which information to transmit.

Sensor utilization can arise as a conflict when individual platforms pursue their own objectives. An example is the operation of active radars on one platform that can interfere with passive radar operation on a nearby platform. The group-level sensor management can avoid this conflict with a priori knowledge of the sensors' characteristics. However, individual platforms can activate sensors based on their own objectives as well. This potential conflict cannot be planned for by the group-level sensor management beforehand, but can be minimized by maintaining good resource-utilization updates from each platform to the group-level sensor management. Furthermore, when a platform intends to operate a sensor that is highly susceptible to interference (*e.g.*, ESM), it can provide this information to the group-level sensor management that can prevent or deactivate conflicting sensors. This conflict resolution by appropriate planning can minimize the occurrence of conflicts. However, in situations that involve self-preservation, conflicts may not be avoidable.

4.3.6 Network-centric warfare

An emerging methodology within the military is “network-centric warfare” that offers a framework to model and address the management of a network of sensors (Figure 15). The focus of network-centric warfare (NCW) is information superiority. This will be achieved with robustly networked battle-space resources that are capable of supporting automation technologies.

A definition of network-centric warfare is:

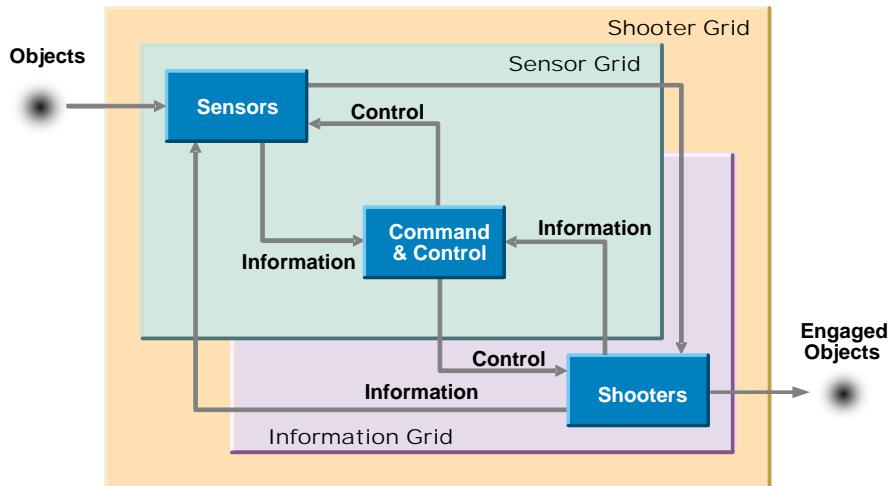


Figure 15: Network-centric warfare

“Network-centric warfare is the conduct of military operations using networked information systems to generate a flexible and agile military force that acts under a common commander’s intent, independent of the geographic or organizational disposition of the individual elements, and in which the focus of the war-fighter is broadened away from individual, unit or platform concerns to give primacy to the mission and responsibilities of the team, task group or coalition” [9]

NCW should shorten the reaction time of the military to act against targets by providing sufficient, accurate and timely data to those that need it. NCW does not merely focus on the network infrastructure necessary to make data available to all. Collecting more information and delivering it faster does not necessarily improve the quality and speed with which decisions are made. NCW is intended to address many aspects: the infrastructure to communicate data, collaborative decision making, rapid replanning, scheduling and allocations. At the core of NCW is information; therefore, surveillance, sensors and sensor management are key components to the success of NCW.

Overseeing the automation of information gathering, analysis, decision making and action of NCW incums to human supervisors [10]. Human supervisory control of NCW tasks is necessary to overcome situations and circumstances that are either too complex to fully plan for or events that were simply never planned for. In this role, the human intermittently interacts with the control system to receive feedback about the current situation and to issue commands to control a process or task. Computer-based control of resources in a potentially hostile, dynamic, and semi-structured environment would be limited to addressing expected situations. Humans, with their innate cognitive skills, are better equipped to address the unexpected, provided that they are not overloaded with irrelevant information. The sensor management system can help the analysis team (humans and computers) by providing it with relevant information delivered in a timely fashion.

4.4 General considerations for sensor management

This section discusses some general issues that need to be addressed by a sensor management system independently of the underlying configuration.

4.4.1 Quality of information

Information quality is a subjective matter that depends on the objectives of the surveillance system, and the precise definition may change, depending on the evolution of the situation. In military applications, for instance, the best information may be the accurate location of threatening targets. In search and rescue, the best information may be the accurate location of a friendly target. The point is that sensor management must utilize high-level analysis of the situation in order to direct resources.

Generally speaking, information quality needs to be defined explicitly by means of a calculable metric for sensor management. In target tracking for instance, this metric should reflect the relative importance of targets and provide an increased measure of quality when resources are diverted from low-priority targets to gain accuracy on high-priority targets.

The quality of information has also a temporal component. In target tracking, for example, greater track accuracy can be achieved by devoting more time to the observation of a particular target. However, this may delay the reporting of the track. It is the role of sensor management to balance the time delays in reporting measurements with the accuracy with which those measurements are computed. This aspect of information quality should also be reflected in the calculable metric.

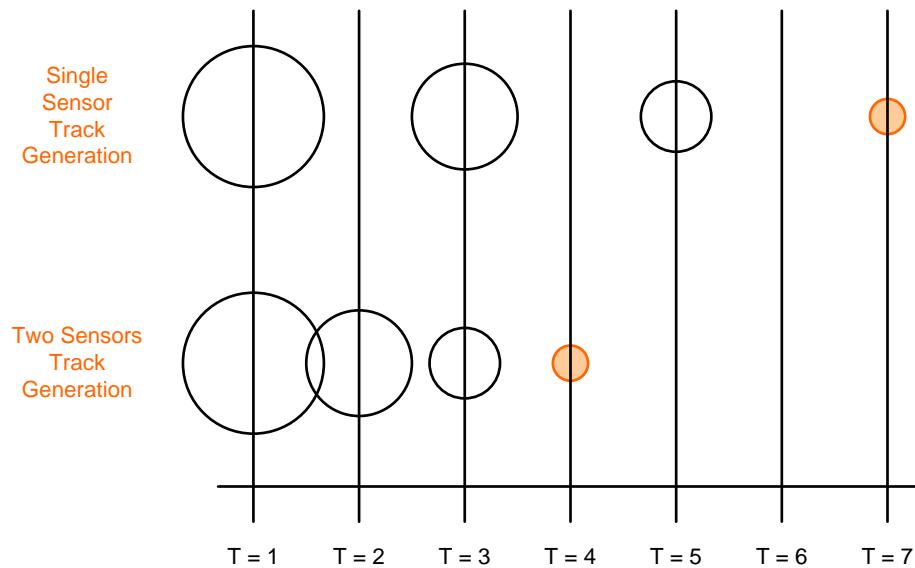


Figure 16: Track generation using one and two sensors

A surveillance system provides an opportunity for gathering better quality information if the sensors are correctly managed. In target tracking, for example, multiple sensors can

be assigned to the same sensing task in order to gather better information in a shorter time than with a single sensor. For instance, consider the case of a single hostile target and two identical sensors (*e.g.*, air/surface search radar such as the Ericsson SeaGiraffe) available to track it. Figure 16 illustrates this example. In the upper scenario (single sensor) measurements made by a single sensor reduce uncertainty in the target track at a fixed rate due to the revisit limitations of the sensor. When a second identical sensor is employed (lower scenario in the figure), target measurements can be made at twice the rate, thereby reducing track uncertainty in a much shorter time. The above example illustrates only one way in which multiple sensors can be utilized to improve sensing performance.

4.4.2 Control time-scale

It should be emphasized that there are two types of control being implemented by the sensor management system, continuous and discrete. The selection of a management strategy occurs in response to new and significant events occurring in the VOI. These events typically happen at irregular or discrete time intervals. Between these intervals, the sensor management system is required to control the sensing resources in a continuous fashion to achieve or maintain the sensing strategy objectives.

Continuous control responsibilities depend on the particular sensors employed and the architecture that is used to implement that control. With highly sophisticated sensors such as ESA, tracking control (*i.e.*, scan pointing) is taken care of by the sensor itself; therefore sensor management need not perform this duty. However, with less sophisticated sensors such as a turret mounted camera, continuous pointing commands may be required to maintain sensor tracking. The control architecture specifies the type of control that is required for each sensor and the means of implementing that control.

4.4.3 Control architecture

Sensor control by the management system is implemented through a control architecture. This architecture is designed according to the level of complexity of the sensing resources and other practical issues of implementation (*i.e.*, hardware configuration, platform configuration, etc.). When ‘intelligent’ sensors (*e.g.*, Electronically Scanned Array (ESA)) are utilized, sensor management control may consist only of high-level commands issued to the sensors. In this case, the simple specification of a target to track is sufficient, as the sensor itself is capable of maintaining the track. In other cases, where the resources require more direct control, the sensor management architecture needs to provide this capability to the management system. This may include a low-level controller capable of providing track guidance for individual sensors.

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5 Hierarchical structure of military sensor management

The military command structure is strictly hierarchical in nature, and this hierarchy is reflected in the coordination and cooperation of military platforms. Vehicles, ships, and aircraft all fall under the chain of command, taking orders from superiors and issuing orders to subordinates. An example of such a hierarchy is shown in Figure 17 for a naval task force. When such a force is deployed to operate in a dynamic environment, the sensing resources located on each of the platforms can work together to maximize overall sensing capabilities. Data are refined and combined (fused) with other data as they are passed up the chain of command. As a result of the hierarchical command structure, the fusion process and therefore the sensor management process is hierarchical in nature (Figure 18).

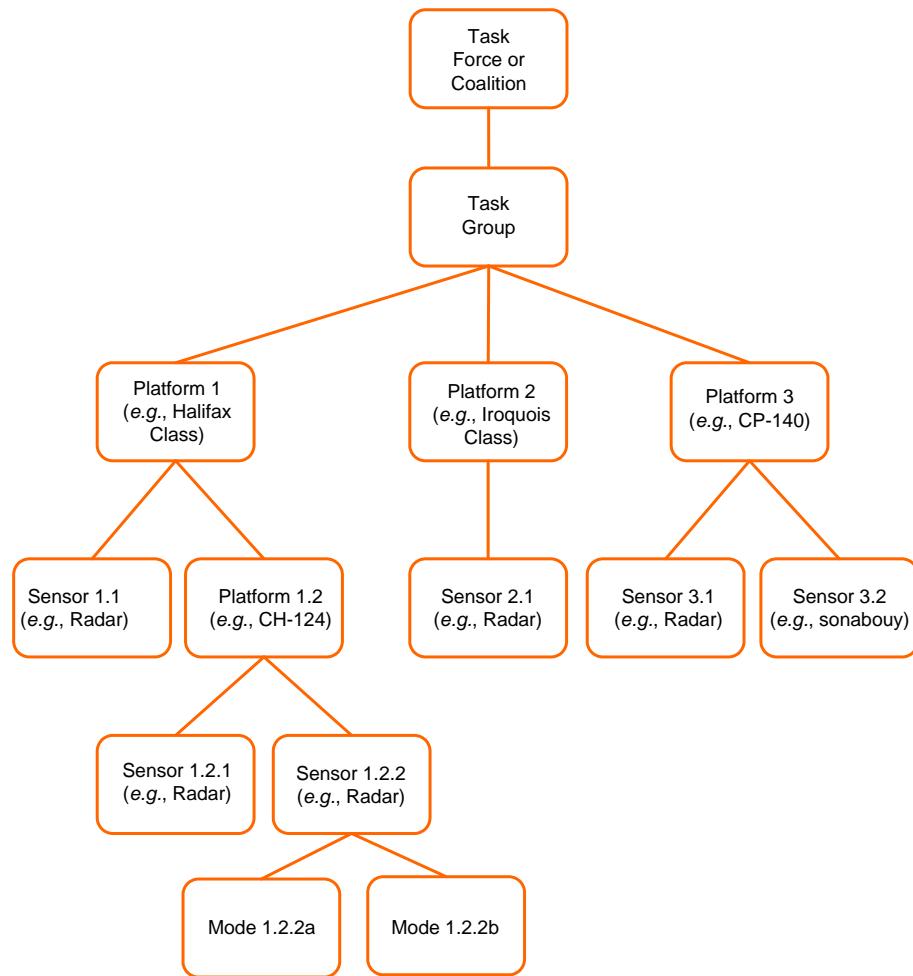


Figure 17: Hierarchy of naval sensing resources

If we consider the sensor management process occurring within a single platform (see Figure 9) we see that sensing resource data are combined (fused) and that high-level analysis of

these data is used by the sensor management system. Figure 9 illustrates such closed-loop sensor management approach within a single military platform.

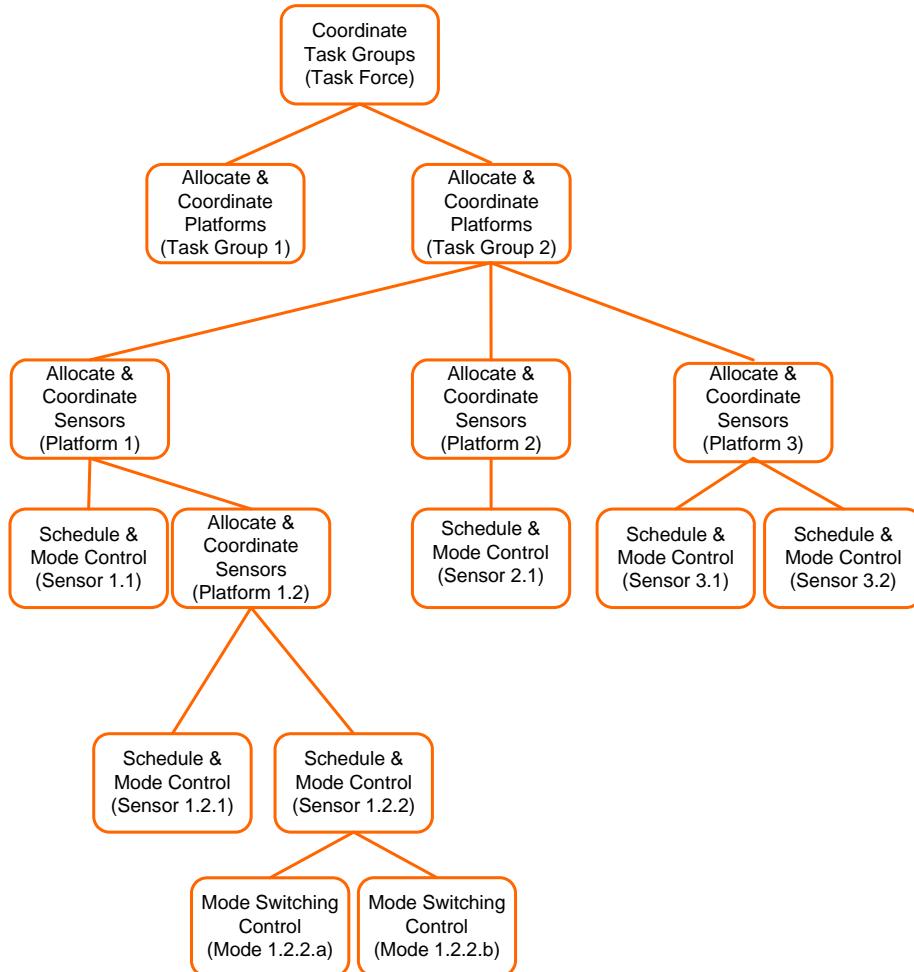


Figure 18: Hierarchy of sensor management problems in military context

If we think of the platform as a resource for the management of a group of platforms then we see that sensor management is not just hierarchical but also recursive. This recursion is illustrated in Figure 12 representing a set of platforms and a group-level sensor management system interacting with all of them. As an example, the platform resources could be frigates with their own internal C². The group-level C² could be a remote command center, another military platform such as a destroyer, or even a command center aboard one of the frigates in the group. If the platforms are viewed as resources for a C², we can see that sensor management at this level is similar to sensor management within the platforms themselves. Here data from sensor resources (platforms in this case) are fused and analyzed, providing input to the sensor management system which then redirects the sensing resources. Sensor management at the group level does not control sensors aboard the platforms directly, but allocates high-level sensing tasks to the platforms. In target tracking, for instance, group-level sensor management may decide which targets each platform should track, but it would

be up to the platforms themselves to decide which sensors to use to fulfill the task.

The function of sensor management at the platform level and the group level differ but the structure is hierarchical and recursive. This recursive structure can be extended to management of groups of platforms (*e.g.*, task forces and multinational coalitions) with exactly the same structure. Force/coalition-level sensor management coordinates the sensing activities of groups of platforms. At each level in the hierarchy, the systems below it are considered as resources, whether they are sensors aboard a platform, platforms within a group or groups within a task force/coalition.

It should be noted that, while the sensor management structure can be described as hierarchical and recursive in nature, we have not explicitly specified how data essential to sensor management (*i.e.*, resource utilization, platform navigation, etc.) are communicated between platforms or how sensor management issues commands (allocates tasks) to the various resources under its control. In addition, we have not specified how the various sensor management systems perform their management duties, *i.e.* control the resources allocated to them.

The decentralized, hierarchical, and recursive nature of this structure will need to be considered when comes the time to select or design a control architecture for sensor management.

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6 Conclusion

This document has described the role of sensor management in the process of data fusion and shown its use within the context of military surveillance operations. Due to the nature of the military command structure, both the data fusion and the sensor management processes are hierarchically organized. Sensor management responsibilities are different at each level of the hierarchy. For instance, sensor management aboard a single platform is concerned with the efficient use of that platform's sensor(s), whereas at the group level, sensor management is concerned with the efficient use of the platforms themselves.

However, as demonstrated, the aim of sensor management in the fusion process remains the same at each level of the hierarchy; that is, to utilize a high-level analysis of the sensor data to direct the resources in order to maximize the achievement of the sensing objectives. Although these objectives are not identical, the interaction of sensor management and the available resources are reproduced at each level. In this sense, sensor management exhibits a recursive organization.

This memorandum has focused on the issues and general characteristics of sensor management in a tactical setting. Central to sensor management, in this context, is the communication between the sensors and the sensor management system. In order to implement the sensor management capability, this communication needs to be facilitated by the control architecture.

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List of Acronyms

C²	Command & Control
CANEWS	Canadian Naval Electronic Warfare System
CCS	Command & Control System
CSR	Conventional Scanning Radar
DDPS	Distributed Data Processing Systems
DSS	Decision Support System
DF	Direction Finding
EMR	Electromagnetic Radiation
EA	Electronic Attack
ECM	Electronic CounterMeasures
EM	Electromagnetic
EP	Electronic Protection
ESA	Electronically Scanned Array
ESM	Electronic Support Measures
EW	Electronic Warfare
FIFO	First In First Out
FIPA	Foundation for Intelligent Physical Agents
FLIR	Forward Looking Infrared
FOV	Field Of View
HCD	Holonic Control Devices
HIT	High Interest Target
HVU	High Value Unit
IR	InfraRed
ISR	Intelligence Surveillance & Reconnaissance
JDL	Joint Directors of Laboratories
LIFO	Last In First Out
LIDAR	Laser Infrared Radar
MAD	Magnetic Anomaly Detector
MSDF	Multi Source Data Fusion
OODA	Observe-Orient-Decide-Act
PWGSC	Public Works and Government Services Canada
RADAR	Radio Detection & Ranging
SONAR	Sound Navigation Ranging
SA	Situation Analysis
SAR	Synthetic Aperture Radar
SM	Sensor Management
UAV	Unmanned Aerial Vehicle
VOI	Volume of Interest

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The military typically operate in large-scale, dynamic, and semi-structured environments. A key challenge facing the military operators in these contexts, is to make the most effective use of the available, but scarce, sensors to gather the most complete and relevant information. This defines the sensor management problem that aims at utilizing the sensing resources in a manner that synergistically improves the process of data acquisition and ultimately enhances the perception and the comprehension of the situation of interest. As part of the Command & Control process, sensor management is about the adaptive coordination, allocation, and control of sensing resources. This memorandum provides a state of the art on sensor management in the context of military tactical surveillance operations. In particular, issues and constraints associated with sensor management in scenarios involving a single sensor, multiple sensors aboard a single platform, and multiple sensors distributed across multiple platforms are discussed.

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